SMALL MODULAR NUCLEAR REACTORS: ECONOMIC SUSTAINABILITY ASSESSMENT

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Contents

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List of Acronyms

AACE American Association of Cost Engineers. 8, 110, 111

AC Alternating Current. 90

ADP Abiotic Resource Depletion Potential. 88

AGR Advanced Gas-cooled Reactor(s). 116

aka also known as. 33, 75, 84, 85, 91, 97, 121, 137, 177, 286, 298

AMR Advanced Modular Reactor(s). 103, 202

AP Acidification Potential. 69, 85

ARIS Advanced Reactors Information System. 104

BWR Boiling Water Reactor(s). 134

CANDU Canadian Deuterium Uranium. 80, 99

CFCs Chlorofluorocarbons. 83

CNC Critical Natural Capital. 53–55, 65

CNNC China National Nuclear Corporation. 104

CPI Corruption Perception Index. 11, 68, 76, 189, 197, 200, 220, 227, 230, 232, 234, 239, 241, 243, 250, 252, 256

CSD United Nations Commission on Sustainable Development. 32, 39, 40

CSP Concentrated Solar Power. 92, 93

DALY Disability Adjusted Life Years. 69, 96, 296

DBEIS Department for Business, Energy & Industrial Strategy. 160, 212

DC Direct Current. 90

DCB Dichlorobenzene. 68, 69, 84–87, 95, 289, 290, 292, 296

DCF Discounted Cash Flow. 175, 216

DECC Department of Energy and Climate Change. 159

DSD United Nations Division for Sustainable Development. 39, 40

e.g. for example. 41, 52–54, 58–60, 62, 64–66, 72, 74, 76–79, 81–93, 95–97, 99, 101, 106, 109, 111, 115, 116, 119, 131, 134–136, 138, 141, 143, 157–159, 161, 168, 172, 183, 195, 196, 202, 211, 212, 222–224, 247, 248, 276, 279, 291, 296

ED Economic Dispatchability. 17, 18, 68, 75, 187, 188, 219, 220, 230, 232, 234, 236, 239, 241, 243, 245, 250, 252

ENSAD Energy-related Severe Accident Database. 97

EP Eutrophication Potential. 69, 85

EPR European Pressurized Reactor(s). 97, 98, 121, 129, 130

FOAK First Of A Kind. 8–11, 14–18, 116–118, 120–136, 139–143, 153–156, 159, 160, 162–166, 175, 177, 178, 181–188, 191–193, 207–210, 215, 220

FPSF Fuel Price Sensitivity Factor. 17, 19, 68, 79, 193, 194, 197, 200, 223, 227, 231, 233, 235–237, 240, 242, 244, 245, 251, 253, 257

GFR Gas Cooled Fast Reactor(s). 93

GHG Green House Gas. 82, 288

GWP Global Warming Potential. 8, 21, 68, 82, 83, 95, 288

GWP100 GWP factors derived considering a time horizon of 100 years. 83

HIR Human Health Impacts from Radiation. 96

HLW High Level Waste. 88

HTGMNR High Temperature Gas Micro Nuclear Reactor. 203, 204, 206, 212, 214

HTGR High Temperature Gas Reactor(s). 93, 202, 204–208, 210, 215, 226

HTP Human Toxicity Potential. 69, 95, 96

HWR Heavy Water Reactor(s). 92

IAEA International Atomic Energy Agency. 72, 103, 104, 115, 224

IAEG-SDGs Inter-agency and Expert Group on SDG Indicators. 40

IDC Interest During Construction. 121, 122, 127

ILW Intermediate Level Waste. 88

INPRO International Project of Innovative Nuclear Reactors and Fuel Cycles. 72, 73

IPA Impact Pathway Approach. 72

IRIS International Reactor Innovative and Secure. 105

IRR Internal Rate of Return. 10, 11, 68, 75, 177, 181–183, 185, 197, 200, 217, 218, 227, 230, 232, 234, 236, 239, 241, 243, 247, 250, 252, 254, 256

LCA Life Cycle Assessment. 72, 96

LCOE Levelised Cost of Electricity. 8, 17, 19, 68, 75, 78, 79, 134, 135, 191–193, 197–201, 205, 221–223, 227, 228, 231, 233, 235–237, 240, 242, 244, 245, 247, 248, 251, 253, 255, 257

LFR Lead-cooled Fast Reactor(s). 93

LLW Low Level Waste. 88

LR Large Reactor(s). 4, 5, 9, 10, 12, 15, 19, 118, 119, 121, 127, 129–133, 136, 142–144, 155, 156, 165, 166, 171, 197, 198, 200, 207, 208, 211, 216, 218, 219, 221–224, 226–248, 250–257

LWR Light Water Reactor(s). 92, 93, 103, 145, 202

MCDA Multi-Criteria Decision Analysis. 72

MDGs Millennium Development Goals. 40

MNR Micro Nuclear Reactor(s). 5, 11–13, 17–19, 28, 202, 203, 205–224, 226–228, 247–257

MSR Molten Salt Reactor(s). 93

MWe megawatts-electric. 34, 35

NEA Nuclear Energy Agency. 115

NNL National Nuclear Laboratory. 35, 103, 105, 173, 183, 192, 193

NOAK Next Of A Kind. 5, 9–19, 116, 121–129, 131–133, 135, 139–143, 153–156, 159, 160, 162–166, 170–172, 174–177, 179–188, 191–194, 198, 206–210, 214–223, 226, 229–237, 239–244, 247, 250–256

NPP Nuclear Power Plant(s). 8, 119–121, 159–161

NPV Net Present Value. 16, 68, 74, 75, 175, 177–180, 197, 200, 216, 217, 227, 230, 232, 234, 236, 239, 241, 243, 245, 247, 250, 252, 254, 256

NSSC Nuclear Safety and Security Commission. 104

O&M Operation and Maintenance. 4, 9, 11, 15, 18, 106, 134–144, 155, 159, 166, 170, 171, 175, 202, 205, 206, 208, 211, 223, 226, 236, 245, 255

OCGTs Open Cycle Gas Turbines. 80

ODP Ozone Depleting Potential. 68, 83, 289

ODS Ozone Depleting Substances. 83

OECD Organisation for Economic Co-operation and Development. 97, 115, 119, 160, 224

POCP Photochemical Ozone Creation Potential. 68, 84, 289

PSA Probabilistic Safety Assessment. 97

PSI Paul Scherrer Institute. 97

PV Photovoltaic. 83, 86, 88, 91, 94, 101

PWR Pressurised Water Reactor(s). 9–13, 15, 16, 19, 35, 36, 97, 98, 100, 104, 116, 119, 121, 125, 134, 135, 138–140, 147, 152, 153, 158–161, 164, 170–174, 195, 197, 198, 200, 204–206, 211, 212, 214, 216–218, 221–223, 226, 227, 229, 255, 256

R-P Reserves-to-Production. 8, 17, 68, 81, 196, 197, 200, 224, 227, 231, 233, 235, 240, 242, 244, 251, 253, 257

RA Risk Assessment. 72

ROI Return on Investment. 17, 18, 68, 75, 183–185, 197, 200, 218, 227, 230, 232, 234, 236, 239, 241, 243, 245, 247, 250, 252, 254, 256, 279

SDGs Sustainable Development Goals. 40, 62, 66

SMR Small Modular Reactor(s). 4, 5, 8–19, 28, 34–36, 67, 91–93, 102–105, 115–129, 131–146, 148, 149, 151–156, 159–167, 169–212, 214–224, 226–248, 250–257

TETP Terrestrial Eco-Toxicity Potential. 69, 86

UK United Kingdom. 3–5, 9–12, 16, 28, 35, 73, 90, 103–105, 115–117, 123, 127–130, 133, 135, 136, 138, 145, 146, 149, 159, 162, 168–171, 173, 175, 176, 181–183, 188–190, 192, 193, 199, 202, 203, 212, 214, 218, 220, 221, 229, 230, 232, 234, 238, 239, 241, 243, 247, 248, 250, 252, 254

UN United Nations. 38, 72, 78

UNECE United Nations Economic Commission for Europe. 34, 36

US United States. 104, 146

USA United States of America. 31

UVB Ultraviolet B. 83, 84

WCED World Commission on Environment and Development. 38

List of Symbols

Am Americium. 99, 101

NH_3 Ammonia. 85

Sb Antimony. 69, 88, 293

bn Billion(s). 117, 130

GBP British Pound Sterling(s). 78, 117, 118, 122, 123, 125, 126, 135, 136, 139, 140, 146, 147, 153, 154, 160, 163, 165, 207–210, 215

CO_2 Carbon Dioxide. 68, 82, 83, 254, 288

CO Carbon Monoxide. 84

C Celsius Degrees. 83, 91–93

Cu Copper. 88

m^3 Cubic meter(s). 69, 88, 100, 287, 293, 297

C_2H_4 Ethylene. 68, 84, 289

GJ GigaJoule(s). 69, 100, 297

GWe Gigawatt(s) Electric. 32, 169

GWd Gigawatt-day(s). 100, 138, 148–151

GWh Gigawatt-hour(s). 69, 86, 96, 295, 296

$GWyr$ Gigawatt-year(s). 97, 98

g Gram(s). 83, 85, 95

h Hour(s). 68, 167, 231, 233, 235, 240, 242, 244, 251, 253, 277–280, 284–286, 291–293, 295, 296

HCL Hydrogen Chloride. 85

KBq KiloBecquerel(s). 296

kg Kilogram(s). 68, 69, 85, 87, 88, 288–293, 296, 298

kgU Kilogram(s) of Uranium. 146, 147

kWe Kilowatt(s) Electric. 115, 117, 118, 122, 123, 125–129, 131, 132, 135, 136, 139, 140, 142, 152–155, 158–161, 163, 165, 173, 174, 207–211, 215, 277–280, 284, 285, 291–293, 295, 296

kWh Kilowatt-hour(s). 68, 69, 78, 83–88, 95, 277–279, 283, 288–293, 296

$MWth$ Megawatt(s) Thermal. 104, 105, 139, 148–151, 202, 203, 218

MWe Megawatt(s) Electric. 8–12, 17, 36, 68, 103–105, 114–118, 121–123, 125, 126, 130, 134–136, 138–140, 145, 146, 148–154, 158–160, 162–164, 167, 169–171, 175, 177, 183, 185, 187, 191, 193, 197, 200, 202–210, 212–221, 224, 226, 227, 229, 230, 232, 234, 236, 238, 239, 241, 243, 245, 250, 252–256, 276, 285, 286

MWh Megawatt-hour(s). 78, 167–169, 176, 177, 183, 192, 193, 199, 205, 212–214, 216–218, 222, 229, 231, 233, 235, 236, 240, 242, 244, 245, 251, 253, 285

CH_4 Methane. 84

μg Microgram(s). 83

mg Milligram(s). 84, 85

min Minute(s). 68, 80, 231, 233, 235, 237, 240, 242, 244, 251, 253, 286, 287

MOX Mixed Oxide Fuel. 150

nm Nanometer(s). 83

Np Neptunium. 99

NO_x Nitrogen Oxides. 84, 85

p Pence. 68, 78, 283

$person-yr$ Person-year(s). 94, 295

PO_4^{3-} Phosphate ion. 69, 85, 291

Pu Plutonium. 99, 101

P_{max} Maximum output power. 80

£ British Pound Sterling. 115, 117, 118, 122, 123, 125–132, 135, 136, 139, 140, 142, 152–155, 158–161, 163, 165, 167–169, 176, 177, 183, 188, 192, 199, 204, 207–210, 213, 215, 229, 276–280, 283, 284

SWU Separative Work Unit(s). 146, 147

m^2 Square meter(s). 69, 86, 291, 292

SO_2 Sulphur Dioxide. 69, 85, 290

TWh Terawatt-hour(s). 94, 295

t Tonne(s). 287

tU Tonne(s) of Uranium. 81, 100, 138, 139, 148–151, 196, 297

tU_{nat} Tonne(s) of Natural Uranium. 148–151

$CFC-11$ Trichlorofluoromethane. 68, 83, 288, 289

U Uranium. 99

UO_2 Uranium Dioxide. 148–151

USD US Dollar(s). 78, 146, 147, 160, 165

$VOCs$ Volatile Organic Compounds. 84

yr Year(s). 68, 69, 81, 86, 196, 230–235, 239–244, 250–253, 279, 287, 291, 295

Abstract

In order to provide decision and policy makers with the necessary tools to assess diverse sustainable energy futures, a set of 30 sustainable energy supply indicators was brought together based on the fundamentals of the so-called 'three pillars of sustainable development' - economic, social and environmental. Similarly, an innovative extra set of 10 indicators was created solely to evaluate the attractiveness of investing in a particular energy technology as it was recognised that for energy technologies to be available their investment projects have to be sufficiently attractive to justify doing so. Later on, upon utilisation of a refined cost-capacity estimation technique, the economics of near term Small Modular Reactors (SMRs) were characterised assuming a UK context. In addition, evidence that economies of scale are only piecewise valid for nuclear technologies was found. Therefore, using a new cost escalation by parts approach, the special case of Micro Nuclear Reactor (MNR) economics was also investigated. As a result, the attractiveness of investment and the techno-economic sustainability indicators of near term SMRs and MNRs were evaluated in a UK context and compared to those of typical large scale light water reactors in a similar context. On one hand, it was found that if SMRs are to be available it is most likely going to be in the form of multiple reactor configurations rather than single one-by-one cases. Results suggest that, if no further cost reductions are demonstrated, single SMRs may only be a more attractive investment than large reactors if suitability for remote locations and/or size of investment are a limitation. On the other hand, acknowledging that they are prone to compete in a different market niche, single MNRs were identified as a potential investment opportunity for large non-domestic electricity consumers, especially for those requiring heat and power. Results indicate that the cost of electricity generated by MNRs could be similar to the price of electricity currently paid by large individual firms. Thus, excluding MNRs which are intended to compete in a different market, the attractiveness of investment of near term SMRs and typical large scale light water reactors was found to be directly proportional to their size or capacity and to improve with multiple reactor configurations. In contrast, the techno-economic sustainability of the three nuclear energy technologies investigated was found to be inversely proportional to their size or capacity.

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Chapter 1

INTRODUCTION

1.1 Sustainability of Nuclear Power

1.1.1 Historical Evolution of the Nuclear Energy Industry

During the early 1970s, the growth rate of nuclear power capacity, at the global level, was of about 30% per year. However, by the late 1970s, this fast growth rate was slowed down by environmentalist nuclear opponents who began to delay the licensing process and forced the nuclear power industry to make some design changes that resulted in cost increments due to the inability of equipment suppliers, contractors and regulators to manage the challenges of the new nuclear power technologies. As a result, the cost and the payback period of nuclear power projects increased and the financing of nuclear power projects became more difficult. Furthermore, also during the 1970s, not only environmentalist nuclear opponents slowed down the growth rate of nuclear power capacity, but also inflation and high electricity costs reduced electricity demand in general [1].

Towards the end of the 1970s, due to its high capital costs, long lead times and the Three Mile Island accident in 1979, the nuclear power industry nearly disappeared in the United States of America (USA). The Three Mile Island Accident was the first major nuclear accident at a civilian nuclear power plant. Although there was no significant release of radioactive material, the psychological impact affected severely the social perception of nuclear power, even in the western world. However, while the global rate of nuclear power expansion slowed down, the nuclear power share of global electricity supply kept increasing until 1987 when it stabilised at an average of 16.1% and remained almost constant until 2003. In relation, the nuclear power share of global electricity supply remained almost constant for those 16 years (1987-2003) due to the Chernobyl accident in 1986 and the deregulation of the electricity market in many countries that evidenced the excess capacity that had accumulated in regulated markets. The lack of need for new capacity, of any kind, put in disadvantage the technologies that did not offer rapid reliable returns, like nuclear power. However, global nuclear power generation grew in the 1990s as the Chernobyl accident led to management and safety improvements, within the nuclear power industry, that resulted in higher availability factors [1].

More recently, the Fukushima Daiichi accident revived negative social perception about nuclear power. In March 2011, the Fukushima Daiichi nuclear facilities, designed to resist an earthquake of magnitude 8.2 [2], were damaged by "The Great East Japan Earthquake", of magnitude 9.0 and by a tsunami that struck a wide area of coastal Japan. The combined effect, of the earthquake and the tsunami, led to the third major nuclear accident. Radionuclides were released to the atmosphere and were also deposited on land and ocean. People within a radius of 20-30 Km had to be evacuated [3]. Although 10 times more radioactive material was released during the Chernobyl accident, the Fukushima accident led to near term actions and long term measures in order to strengthen the overall safety of nuclear power [2, 3]. Finally, as of late 2017, the global nuclear power capacity reached 392 GWe and the nuclear power share of global electricity supply dropped to approximately 10% [4, 5].

1.1.2 Large Scale Nuclear Power

Throughout its relatively short history, of about 50 years, projections for nuclear power have varied in some regions from enthusiastic to pessimistic [1]. On one hand, for some, nuclear power is a sustainable energy technology and its removal would imply a loss of flexibility and diversity for the energy mix. On the other hand, for others, nuclear power does not reconcile the three pillars of sustainable development. In other words, there is a general disagreement regarding the role of nuclear power [6]. In consequence, as agreed in the 9^{th} session of the United Nations Commission on Sustainable Development (CSD): "The choice of nuclear energy rests with countries" [7].

Projections made by the International Atomic Energy Agency in 2020 [8] suggest that the nuclear power share of global electricity production could be as low as 6% and as high as 11% by 2050. A large number of reactors are scheduled to be retired around 2030 and beyond, particularly in North America and Europe [8]. Without new investment, nuclear power in advanced economies could fall by two-thirds by 2040 [9]. The sustainability of nuclear systems that are currently in operation is questioned by the public and by some decision makers, mainly for the following reasons (not listed by order of relevance) [1, 7, 10, 11, 12]:

1. Energy security.
    - Uncertainty regarding the "uninterrupted availability of energy sources at an affordable price" [13].
        - Uranium is a limited resource and, in most cases, it has to be imported.
2. Environmental impacts and climate change.
3. High capital cost.
4. Intergenerational equity.
    - "Future generations who were neither responsible for the decisions to build nuclear reactors nor enjoyed the benefits of electricity, will nevertheless have to bear both risks and costs of nuclear decommissioning and waste management" [10].
5. Investment risks.
    - For example, political support (if applicable) or financial incentives (if there are any) might be withdrawn.
6. Long lead times.
7. Nuclear waste management and transport.
8. Proliferation of nuclear weapons (also known as (aka) nuclear proliferation).
9. Safety within the nuclear fuel cycle and the impact on human health.

These concerns are legitimate, but possibly solvable [14]. Anxiety about nuclear power is often a consequence of exaggerations and/or statements that are demonstrably false [6]. Recent studies suggest that, in a high energy consumption scenario, nuclear power might play an important role towards meeting climate change targets. According to the International Energy Agency [9], along with significant investments in efficiency and renewables, a clean energy transition as aggressive as that required to achieve the goals of the Paris Climate Change Agreement could require an 80% increase in global nuclear power production by 2040, relative to 2018 levels.

1.1.3 Small Modular Reactors

The international agenda focuses on the eradication of extreme poverty through the achievement of certain goals among which we can find: access and adequate availability of energy services. In fact, according to the United Nations Economic Commission for Europe (UNECE), the three main impediments to achieving a sustainable energy future are: (1) remote off-grid locations, (2) on-grid access with intermittent supply due to poor infrastructure or fuel supply problems and (3) affordability issues [14]. Similarly, as stated in "The 2030 Agenda for Sustainable Development" [15], in order to shift our world on to a sustainable and resilient path we need to take urgent action to combat climate change by promoting investment in energy infrastructure and clean energy technologies. In relation, nuclear energy technologies are net zero carbon and, over the past 50 years, the use of large scale nuclear power has avoided more than 60 Gigatonnes of global carbon dioxide emissions [9]. However, large nuclear power units are not suitable for remote off-grid locations, require a considerably high up-front capital investment and have a relatively long construction period. In other words, the sustainability of large scale nuclear power units remains arguable. Therefore, considering all the previous, the sustainability of the SMR technology must be investigated, as SMRs could potentially contribute to the alleviation of extreme poverty and promote a more sustainable future.

SMRs must have an electrical capacity limited to $\leq$300 megawatts-electric (MWe) per module and are meant to take advantage of module factory fabrication. Moreover, SMRs aim to present the following attributes [16]:

1. **Adequate for small grids and, in some cases, for remote off-grid locations:** due to their reduced electrical capacity, compared to large scale nuclear, SMRs could be suitable for a wider range of grid sizes. Similarly, SMRs with sufficiently low electrical capacities ($\ll$300 MWe) could be suitable for remote off-grid locations as they would not be as restricted as large nuclear power units by the access to large bodies of water.

2. **Better affordability:** SMRs could be a more manageable investment than large nuclear power units and might require less capital investment before producing returns. Therefore, SMRs could offer shorter payback periods [17].

3. **Better quality and higher efficiency:** the majority of SMRs are likely to be built in a controlled factory setting and, therefore, an improvement in quality

and efficiency could be more easily attained by SMRs than by large scale reactors which require significant on-site construction.

4. **Easier financing:** the small size, high efficiency and passive safety systems of SMRs might lead to easier financing, in comparison with large nuclear reactors.
5. **Improved passive safety features:** taking advantage of their small size, SMRs are designed with a high level of inherent safety in case of malfunction.
6. **Lower radioactive inventory:** smaller reactors could lead to smaller radioactive inventories per reactor, compared to large scale nuclear. However, it must be noted that, this is not likely to be the case on a per MWe basis.
7. **On-demand capacity and high mobility:** capacity can be added as required and modules could be easily removed at the end of their lifetime.
8. **Quicker construction:** SMRs have the potential for shorter lead times than large nuclear reactors [17].
9. **Reduced land use:** SMRs are likely to require significantly less space than large nuclear power units, on per reactor basis, and they could be placed underground. Nonetheless, it must be acknowledged that, SMRs might require more space per MWe capacity than large reactors.

"The SMRs that are closest to commercial operation and represent the most viable options to pursue are integral PWRs, drawing on existing technology and global capability" [17]. Furthermore, only considering electricity applications, the UK's National Nuclear Laboratory (NNL) has estimated a potential global market for the SMRs of 65-85 GWe by 2035, with a value of £250-£400 billion [17].

1.2 Research Question

Could the economic sustainability of SMRs be better than that of large scale reactors?

1.3 PhD Research Project Objective

Evaluate the economic sustainability of the SMR technology, within a UK national context, upon selecting and measuring a suitable set of economic sustainability indicators. Later on, compare results with the economic sustainability of large scale nuclear power.

1.4 Chapter Summary

Sustainability of Nuclear Power

- High capital costs, long payback periods, geopolitical distribution of uranium reserves, environmental concerns and the negative impact of the three major nuclear accidents (Three Mile Island, Chernobyl and Fukushima) on social perception have limited the nuclear power share of global electricity supply to approximately 10-15% since 1987.

- Up to date, there is a general disagreement regarding the role of nuclear power and, therefore, "the choice of nuclear energy rests with countries" [7]. Nonetheless, concerns regarding nuclear power are often a consequence of statements that are demonstrably false.

- According to the UNECE, the three main impediments to achieving a sustainable energy future are: (1) remote off-grid locations, (2) on-grid access with intermittent supply due to poor infrastructure or fuel supply problems and (3) affordability issues [14]. Similarly, as recognised by the United Nations [15], we urgently need to promote investment in energy infrastructure and clean energy technologies in order to combat climate change. In relation, although nuclear energy technologies are net zero carbon, the sustainability of large scale nuclear power remains arguable given that, among other reasons, it is not suitable for remote locations and it requires a high up-front capital investment. Therefore, the sustainability of SMRs must be investigated as these may contribute more than large scale nuclear power towards a sustainable energy future.

- SMRs are an emerging nuclear energy technology, most likely PWR based, with capacities of up to 300 MWe. Moreover, SMRs aim to take advantage of module factory fabrication (economies of series production) and co-siting economies.

Chapter 2

SUSTAINABLE DEVELOPMENT

2.1 From Development to Sustainable Development

In order to assess the economic sustainability of any energy supply technology we first have to define what is sustainable development and, as a result, what is economic sustainability. At the same time, to fully understand the meaning and the scope of sustainable development, we have to comprehend that the concept of sustainable development arises from joining two independent terms: sustainable and development. On one hand, "the satisfaction of human needs and aspirations is the major objective of development" [18]. On the other hand, in this context, the term sustainable makes allusion to the ability of an action or a process to be maintained or kept going [19]. Consequently, sustainable development is the uninterrupted satisfaction of human needs and aspirations over time.

Historically, before the boom of sustainable development, it all started with the determination of the scope of development/human well-being. The development of the industrialised world focused on economic growth. This is, human well-being was directly associated with material production. Later, by the early 1960s, the ever-widening gap between industrial countries and poor societies caused by industrial capitalism made clear that social objectives, like fair income distribution, were distinct and as important as economic growth in contributing to human well-being. Afterwards, in the 1980s, due to the destructive environmental effects of the prevailing economic growth approach, environmental degradation was identified as a barrier to human development. This is, by the 1980s the scope of development/human well-being was set to include not only an economic and a social dimension, but also an environmental dimension [20, 21].

Once the scope of development/human well-being was more or less settled and within an environmental movement, the concept of sustainable development had one of its earliest formulations in the 1980s World Conservation Strategy [22]. The document, presented by the United Nations (UN) Environment Programme, the World Wildlife Fund and the International Union for Conservation of Nature and Natural Resources, aimed "to help advance the achievement of sustainable development through the conservation of living resources" [22]. Similarly, within the 1980s World Conservation Strategy, it was recognised that in order to satisfy human needs it is necessary to account for economic, social and environmental factors in the short and in the long term. In other words, development was now desired not just in the short term, but in the long term as well (See Figure 2.1). However, it would not be until 1987, as a result of the report "Our common future" [18] of the World Commission on Environment and Development (WCED), that the concept of sustainable development would gain the wide recognition it has today [20]. Within the report "Our common future", commonly referred to as "the Brundtland Report", the WCED defined sustainable development as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [18]. This definition of sustainable development would later become the most widely accepted definition, as it presents a framework for change rather than a path to achieve sustainable development [20].

In order to complement the work done in 1987 by the WCED, the 2002 World Summit promoted "the integration of the three components of sustainable development – economic development, social development and environmental protection – as interdependent and mutually reinforcing pillars" [23]. The so-called 'three pillars' of sustainability would not just confirm the scope of development/human well-being, but also the interlinkages between these three component elements would make clear that it seems impossible to improve a particular component element of sustainable development without having consequences elsewhere [10]. Actions in one pillar of sustainable development will have impacts on one or more other pillars [6]. Therefore, in the pursue of sustainable development, some detriment of the planet is inevitable. Sustainable development can only be achieved by following the path that offers the best trade-offs between different sustainability aspects [10].

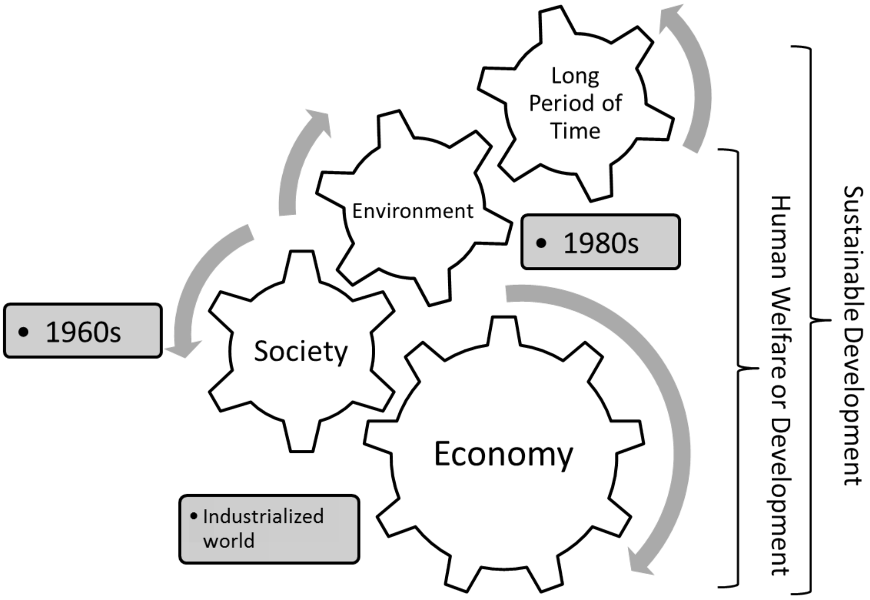

Figure 2.1: Schematic Representation of Sustainable Development.

2.1.1 Measuring Sustainable Development

Once the concept of sustainable development was defined and its scope was reasonably delineated, now the priority was to find out how to achieve sustainable development and how to measure our progress towards achieving it [20]. Consequently, considering that indicators of sustainable development would be important to increase focus on sustainable development and to assist decision makers in the adoption of sustainable development policies, the quest for indicators of sustainable development started since the early 1990s [24].

The action programme adopted by the 1992 Rio Earth Summit, Agenda 21, called for countries, international organisations and non-governmental organisations to develop the concept of indicators for sustainable development. Following Agenda 21, the United Nations Division for Sustainable Development (DSD) prepared a specific work programme on indicators, that was adopted by the CSD [24]. In consequence, in 1996 the CSD published the first edition of the so-called "blue book" [25], an initial set of 134 indicators grouped in four major categories: social, economic, environmental and institutional indicators. These indicators were suited to country-specific conditions and were meant to be used by countries to track their progress towards nationally defined goals of sustainable development. Subsequently, from 1996 to 1999, the indicator set was pilot tested voluntarily by 22 countries in order to evaluate the first CSD indicator set. Most countries found the indicator set to be too large to be manageable and that the first edition of the "blue book" was not suited to emphasise policy issues and linkages. However, before a revised set of 58 indicators could be presented in 2001 by the CSD [7], in the year 2000, the United Nations Millennium Declaration [26] was signed by 189 countries. The signatories of the Declaration committed themselves to eradicate extreme poverty in all its forms, by 2015. Furthermore, in order to track progress towards this commitment, a set of 8 goals (known as the Millennium Development Goals (MDGs) [27]) was created among 21 targets (some of them related to sustainable development) and 60 indicators [28].

Later on, in 2002, the World Summit on Sustainable Development recommended further work by countries on indicators for sustainable development in agreement with national conditions and priorities [23]. In response, the DSD decided that a revision of the CSD indicators would be helpful for countries aiming to develop and implement national indicators for sustainable development [24]. Hence, a third set of CSD indicators, following those published in 1996 and 2001, would be published in 2007 [29]. This third set of CSD indicators was comprised of 96 indicators with a subset of 50 core indicators that were no longer organised in four categories in order to emphasise the multi-dimensional nature of sustainable development [24, 29]. Nevertheless, more recently, with the intention of completing what the MDGs did not achieve, the United Nations General Assembly presented the document “Transforming Our World: The 2030 Agenda for Sustainable Development” [15] in September 2015. Within the 2030 Agenda for Sustainable Development, 17 Sustainable Development Goals (SDGs) and 169 targets in line with the three dimensions of sustainable development, to be accomplished by 2030, were introduced. In relation, prior to the publication of the SDGs, following its forty-sixth session, the United Nations Statistical Commission created an Inter-agency and Expert Group on SDG Indicators (IAEG-SDGs) that was tasked to develop and implement the global indicator framework for the SDGs and targets of the 2030 Agenda for Sustainable Development [30]. As a result, in 2016 the IAEG-SDGs finalised the indicator framework for the 2030 Agenda for Sustainable Development, with a total of 230 indicators [31]. A year later, the global indicator framework was adopted by the United Nations General Assembly.

Finally, as it has been shown in this Subsection, the creation, selection and implementation of indicators of sustainable development is a dynamic process. As of December 2005, the Compendium of Sustainable Development Indicator Initiatives, a database maintained by the International Institute for Sustainable Development, contained over 600 indicator initiatives. However, given that these indicator sets were mainly produced by countries, they were intended to be used only at the national level. In other words, indicators of sustainable development are not independent of their object of study (for example (e.g.) countries, technologies, etc.). Similarly, indicators of sustainable development depend on time and location given that human needs are socially and culturally determined [18, 20, 24].

2.2 Economic Sustainability

Following the Brundtland Report, diverse groups and organisations adopted the concept of sustainable development and gave it their own interpretation. In consequence, regarding the conceptual and operational content of the term, there is appreciable disagreement between economists and ecologists. Due to differences in disciplinary perspectives, some interpretations of sustainable development prioritise economic objectives (weak sustainability), while others prioritise environmental protection (strong sustainability). The opposing models of weak and strong sustainability are based on different conceptions of capital theory. On one hand, weak sustainability is based on the neoclassical theory of economic growth and capital accumulation and its extension to include non-renewable resources (Robert Solow's and John Hartwick's school of thought). On the other hand, strong sustainability relies on biophysical principles and the thermodynamic foundation of a steady-state economy (Herman Daly's school of thought). Both coincide with the economic objective of constant consumption per capita, but they have opposite opinions regarding the substitution of natural resources [32].

Weak sustainability highlights the need to preserve the economy's generalised capacity [32]. Assuming that the economy's productive capacity only depends on its net financial assets and also assuming that certain levels of consumption are associated to particular standards of living; according to weak sustainability, economic sustainability is the obligation to at least preserve the economy's productive capacity (total stock of assets), while promoting constant levels of consumption per capita (standards of living) for future generations [32, 33, 34]. Moreover, this weak sustainability approach assumes that natural resources and reproducible capital can substitute each other, in terms of the well-being they generate [35]. Similarly, Solow's and Hartwick's school of thought states that all resource rents must be invested in reproducible capital in order to achieve the desired constant consumption path.

In contrast, although it also aims for a constant consumption per capita, strong sustainability accentuates the need to maintain the stock of natural capital rather than total capital [32, 36]. According to Daly's school of thought, the economy's productive capacity could increase indefinitely due to increasing knowledge and technical improvement. Nonetheless, Earth's physical dimensions are limited. “In a finite world nothing physical can grow forever” [36]. In other words, the economy's stocks and throughput are limited by space and by environmental quality and resources. Consequently, from an ecosystem perspective, strong sustainability states that it is the total stock of natural capital that must remain constant over time. This implies the preservation of an environmental quality that depends on “the stocks of biological resources, ecosystem space, nutrients available, and other environmental assets that are essential for the integrity of the ecosystem, and provide use and non-use values to society” [32].

In order to make of strong sustainability an operational principle, several authors have interpreted the constant natural capital rule as the strict preservation of every single environmental asset. Nonetheless, in general, strong sustainability does not imply the preservation of every single natural asset [32]. The foundations of sustainable development state that the ecosystem's overall integrity must be sustained and that this does not imply that resources should not be used [18]. In order to maintain the integrity of the environment, sustainable development requires the maintenance of natural assets above a critical level, rather than the preservation of the environment as it is. Therefore, as shown by [32], economic growth, environmental conservation and social welfare are not mutually exclusive. In fact, the original Solow/Hartwick model of weak sustainability can be modified in order to minimise the usage of non-renewables, while achieving a constant level of consumption per capita [32, 37]. Consequently, the weak sustainability model is the one that most resembles the foundations of sustainable development and provides a sustainability framework that can be enriched in order to consider a broader concept of economic sustainability.

2.2.1 Preservation of the Productive Capacity of an Economy

“The productive capacity of the economy can be thought of as the maximum level of production of goods and services that can be generated” [38], essentially the supply side of the economy [39]. Moreover, the productive capacity depends upon physical and technical factors like the economy's: natural resources, physical capital goods (including state of technology), size and productivity of labour force, and entrepreneurship [38, 39, 40, 41]. Therefore, assuming that we can do the valuation correctly, we can calculate the total value of the assets of an economy [34]. Furthermore, according to [34] economic sustainability is the preservation of this total value of the stock of assets of an economy. Consequently, the reduction of one asset must be followed by an increase in other asset(s). Aligned with a weak sustainability approach, the previous implies that trade-offs are possible between reproducible capital goods and natural resources [34].

2.2.2 Externalities and the Need for Policy Interventions

"An externality is usually defined as an unintended side effect of a decision that has not been included in the basis for the decision simply because the effect will not affect the decision maker" [34]. In the view of Karl-Goran Maler [34], material production is inevitably connected with negative externalities given that as economic activity increases, more resources are extracted and more waste has to be discharged back to the environment. Moreover, in the presence of externalities, the market is not able to allocate resources efficiently and there is a need for policy interventions. Nevertheless, apart from market failures related to the lack of well-defined private property rights, occasionally, natural resources are managed inefficiently due to government policies on taxes, subsidies, exchange rates, prices, and others. In consequence, economic growth will accentuate externalities unless we internalise them through the implementation of effective policies [34].

2.2.3 Socially Optimal Rate of Extraction of Exhaustible Resources - Hotelling's Rule

On one hand, as previously implied, environmental protection does not mean that resources should not be used. In the pursue of sustainable development, we are allowed to use natural resources, as long as we maintain natural assets above a critical level. On the other hand, in 1865 William Stanley Jevons argued in his book "The Coal Question" [42] that improving the efficiency of an economy, so that less exhaustible resources are needed to produce the same goods and services, will not necessarily reduce the demand for non-renewable resources. According to the so-called Jevons' Paradox, by rendering the employment of exhaustible resources more profitable, the demand for these resources is increased. In other words, exhaustible resources are depleted too quickly if their price is prevented from rising [43]. Consequently, extraction of exhaustible resources must be forbidden at certain times, if depletion of exhaustible resources is to be prevented. This is, the conciliation of economic growth and environmental protection is only possible if exhaustible resources are exploited at a socially optimal rate.

In 1931, Harold Hotelling [44] determined that an optimal rate of extraction of exhaustible resources is achievable, if the percentage rise in rents from exhaustible resources is equal to the market interest rate:

$$\frac{\frac{d(f(t)-a(t))}{dt}}{(f(t)-a(t))} = \frac{\frac{dp(t)}{dt}}{p(t)} = r \tag{2.1}$$

Where

- t: For a given time scale (usually years), t is the time elapsed since the present time $t = 0$.
- $f(t)$: Market price per unit of exhaustible resource, at time t.
- $a(t)$: Costs of extraction and market placement per unit of exhaustible resource, at time t.
- $p(t)$: Net price received after subtracting the costs of extraction and market placement (also known as capital gain or rent) per unit of exhaustible resource, at time t.
- r: Market interest rate at $t = 0$. If changes in this rate are anticipated, particularly for remote future estimations, a suitable interest rate must be estimated. For example, the average market interest rate of all the time steps considered.

Following Equation 2.1, Equation 2.2 fixes the rent (or capital gain) per unit of exhaustible resource at different times as follows:

$$p(t) = p_0 e^{rt} \tag{2.2}$$

Where

- $p_0 = p(0) = (f(0) - a(0))$: Is the rent per unit of exhaustible resource, at time $t = 0$.

Owners of exhaustible resources, usually adjust their extraction plans so as to maximise the present value of their expected future income. During periods where the rent from a unit of an exhaustible resource increases at a slower rate than the market interest rate, firms elevate their rate of extraction of the exhaustible resource in question. In this scenario, a unit of the exhaustible resource is more valuable if it is extracted in the present than if it is left in its reservoir for future sales (See Equation 2.3).

$$\frac{\frac{dp(t)}{dt}}{p(t)} < r \rightarrow High\ extraction\ rate \tag{2.3}$$

On the contrary, during periods where the rent from a unit of an exhaustible resource increases at a faster rate than the market interest rate, firms decrease their rate of extraction of the exhaustible resource in question. In this scenario, a unit of exhaustible resource is more valuable if it is left in its reservoir for future sales than if its extracted in the present (See Equation 2.4).

$$\frac{\frac{dp(t)}{dt}}{p(t)} > r \rightarrow Low\ extraction\ rate \tag{2.4}$$

Lastly, if the rent from a unit of an exhaustible resource increases at a rate equal to the market interest rate (Hotelling's rule), units of the exhaustible resource in question are worth the same if they are extracted in the present or if they are left in their reservoirs for future sales. Therefore, the Hotelling rule assures a socially optimal rate of extraction of exhaustible resources, as the extraction, of a given exhaustible resource, becomes dependent only upon the demand for the resource. Theoretically, if the Hotelling condition was fulfilled, the market price of exhaustible resources would increase continuously at variable rates (See Equation 2.2), forcing demand for exhaustible resources to decrease at a rate that would depend upon the elasticity of the demand for exhaustible resources. Similarly, rising prices of exhaustible resources would encourage the development of alternative processes to produce goods or provide services and the usage of alternative resources [43].

Equation 2.2 should not be interpreted as "the socially optimal rate of extraction of any non-renewable resource is such that its price increases at a rate equal to the interest rate" [43], as it is the return (or capital gain) per unit of exhaustible resource which should increase at a rate equal to the market interest rate, not the market price. According to the Hotelling rule (Equation 2.2), the market price of a non-renewable resource increases at a rate equal to the market interest rate if and only if the costs of extraction and market placement increase at an equal rate. In order to illustrate the previous, let us analyse an alternative representation of the the Hotelling rule, by substituting the exponential term of the right hand side of Equation 2.2 with its Taylor expansion around $t = 0$:

$$p(t) = p_0 \left(1 + rt + \frac{(rt)^2}{2} + \frac{(rt)^3}{6} + \frac{(rt)^4}{24} + \frac{(rt)^5}{120} + O(t^6)\right) \tag{2.5}$$

For sufficiently small market interest rates and time intervals ($rt << 1$), Equation 2.5 can be approximated as follows:

$$p(t) = p_0(1 + rt) = (f(0) - a(0))(1 + rt) \tag{2.6}$$

As implied by Harold Hotelling in [44], the extraction costs of exhaustible resources might increase with time and resource depletion. Nonetheless, if they increase, the rate at which the costs of extraction could increase is not necessarily restricted to the market interest rate. Therefore, in general, Hotelling's rule does not imply that the market price of exhaustible resources should increase at a rate equal to the market interest rate:

$$p(t) = p_0(1 + rt) = (f(0) - a(0))(1 + rt) \neq f(0)(1 + rt) - a(0)b(t) \qquad (2.7)$$

If $b(t) \neq (1 + rt)$.

2.2.4 Constant Consumption Path - Hartwick's Rule

After the first oil shock, making assumptions that are conventional in the theory of growth with exhaustible resources, in [45], John Hartwick proved that a constant stream of consumption is possible for a society that produces current output, which can be consumed or invested, under constant returns to scale and uses as inputs a given supply of labour, stock of capital and withdrawals from a finite stock of a non-renewable resource [33]. Assuming that: there is a single produced output, there is no population growth, the supply of labour is constant, there is no technological progress [33], all inputs are essential for producing a positive output of a single produced commodity (Cobb-Douglas technology), all inputs are mutually substitutable, marginal productivities are positive, the average marginal extraction costs of exhaustible resources are constant, reproducible capital does not depreciate and all production (current output) is consumed, invested or spent in the extraction of exhaustible resources; Hartwick's rule establishes that it is possible for a society to maintain a constant consumption per capita if:

1. It fully employs its capital stock and labour supply [33].
2. The shadow value of a unit of the exhaustible resource increases at a rate equal to the marginal net product of reproducible capital[1] [33]. This is the Hotelling Rule [44], merged with a neoclassical theory of investment where the marginal product of capital is a direct measure of the market interest rate [46].
3. It follows a specific investment policy: all the competitive rents from the exhaustible resource are invested in reproducible capital goods [33, 45].

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[1] Marginal net product of reproducible capital expressed as a ratio of the price of a unit of reproducible capital [46].

According to Hartwick's findings, the accumulation of reproducible capital would offset the decline in the flow of resource inputs [45]. Moreover, as shown in [47, 48], Hartwick's results can be extended to include more than one resource pool, consider depreciation of capital stock and include the presence of a renewable natural resource. In this extension of Hartwick's rule, constant consumption per capita is still achieved if the investment policy is modified as follows:

$$Investment_K = f_E \times E + f_R \times (R - N) \tag{2.8}$$

Where

- $Investment_K$: Investment in reproducible capital goods.
- f_E: Net marginal product (return) per unit of exhaustible resource.
- E: Units of the exhaustible resource going into the economy.
- f_R: Net marginal product (return) per unit of renewable resource.
- R: Units of the renewable resource going into the economy.
- N: Units of the renewable resource going into the environment, arising from natural growth.

From Equation 2.8, while all the rents from exhaustible resources still have to be invested in reproducible capital goods, the rents from renewable resources must not be invested in reproducible capital goods unless their rate of harvest exceeds the rate of natural growth of the renewable resource in question. Similarly, for exhaustible resources, the Hotelling rule remains the same, in order to achieve a socially optimal rate of extraction. However, in the case of renewable resources, the need for a percentage rise in rents is subject to the rate of harvest and the rate of natural growth of the renewable resource in question.

On one hand, Hartwick's findings were initially limited to a no technological progress scenario, but sustainable development might require the usage of technology to enhance the needs of current and future generations. Therefore, in [32], Werner Hediger highlighted the importance of human capital and also extended Hartwick's results to consider the state of technology as an additional factor of production, allowing technological progress, while constant consumption per capita is still achieved. On the other hand, we do not know if the previously mentioned models of economic sustainability are robust against population growth or highly variable extraction costs of exhaustible resources. At the simplest level, constant consumption per capita would not be permanently maintainable unless technological progress is comparable with the rate of population growth [33]. Nonetheless, “we have very little to go on in the making of decisions with very long-run consequences. The tendency is to allow short-run considerations to dominate because we can grasp them better” [33]. Consequently, the limitations of Hartwick's findings, and of the extensions of his models, should not stop us from using them in the quest of economic sustainability if only as a, better than average, rule of thumb.

2.2.5 Neoclassical Economics Assumptions

The ideologies and theories, previously presented within this section, belong to the school of neoclassical economics and, therefore, rely on the concept of ‘general equilibrium’, where supply and demand are balanced in all markets [21]. Thus, the neoclassical economics framework assumes that perfectly competitive conditions exist and that production and consumption decisions are taken efficiently. Consequently, among other conditions, a state of general equilibrium implies:

1. “**Consumer Theory:** individual consumers maximise their utility (or welfare) by making rational choices among goods and services available in the market” [21].

2. “**Producer Theory:** individual producers maximise their profits by making rational choices about what outputs to produce, what inputs to use and what technologies to adopt” [21].

3. “**Market Behaviour:** individuals act independently, using full and accurate information” [21].

4. “**Perfect Competition:** large numbers of consumers compete for homogeneous goods and services, which are produced by many small firms. Neither consumers nor producers have market control” [21].

In the view of neoclassical economics, organisation and allocation of scarce resources is the central economic problem and efficiency is the most relevant criterion. Moreover, within this context, efficiency makes reference to the optimal usage of available resources in order to maximise individual utility [49]. To summarise, neoclassical economics and the concept of ‘general equilibrium’ assume that: efficient prices reflect true marginal social costs, scarce productive resources are allocated in such a way that output is maximised, and consumers maximise their utility by making efficient choices [21].

2.2.6 Broadening the Concept of Economic Sustainability

As we have seen, theoretically, a constant consumption path can be achieved while preserving the economy's productive capacity, if the reduction of one asset is accompanied by an increase in some other assets. However, the productive capacity of an economy not just depends on physical and technical factors, but it also depends upon economic and institutional forces, such as: income distribution, wage rates, inflation, consumer's preferences, relative prices, and so on [39]. Similarly, the perfectly competitive conditions, assumed by neoclassical economics, rarely exist in the real world. In reality, market prices for goods and services diverge from efficient prices due to monopoly practices, externalities and interventions to the market process through taxes, duties and subsidies. As a result, consumption and production decisions might not be efficient [21]. Furthermore, as highlighted by [32], Solow's, Hartwick's and Daly's conceptions of intergenerational equity implicitly neglect stock pollution. Nonetheless, global warming and climate change, almost certainly, can be attributed to human influence [50]. Therefore, neglecting pollution, in all its forms, is not an option. Finally, the application of Hartwick's rule would not guarantee the maintenance of natural capital stocks above critical levels, it would only assure that the stocks of exhaustible natural resources would asymptotically approach zero as time tends to infinity.

Thus, aiming to broaden the concept of economic sustainability, within this work, economic sustainability will make allusion to the potentially not fully achievable, intergenerational equity-related obligation to maintain intact the economy's net financial assets, while promoting the highest permanently maintainable consumption per capita by complying with the following:

1. The reduction of an exhaustible resource must be accompanied by investments in physical and/or human capital, with the intention to maintain the total value of the stock of financial assets non-decreasing [34].
    - 1.1. “The damage to future generations from present resource use, must be quantified, valued” and small [34].
        - 1.1.1. If the exploitation of a natural resource will bring uncertain and potentially irreversible consequences, the resource must never be allowed to be depleted or degraded [34].

    1.2. The size of the investment in reproducible capital (including state of technology) and/or human capital must be comparable with all the rents from exhaustible resources [32, 48].
    1.3. The percentage rise in rents from exhaustible resources should be equal, at any instant in time, to the market interest rate [33, 45, 47, 51].
    1.4. Accumulated and new reproducible capital goods must be fully employed [33].

2. The rate of harvest of renewable resources shall not exceed the rate of natural growth of these resources [48].
    2.1. If condition 2 is violated, income resulting from the excess rate of harvest of renewable resources will have to be invested in reproducible capital goods. Similarly, failure to comply with condition 2 will result in the rise of rents from renewable resources, in order to reduce consumption [48].

3. With the intention to achieve and sustain a balanced economy, necessary for a constant consumption path, and aiming to adhere to the foundations of sustainable development, producers of goods and services should comply with the following conditions:
    3.1. Employ as much people as possible in order to promote full employment.
    3.2. Wages growth rate must remain reasonably stable [36, 38].
    3.3. Goods and services resulting from the reduction of an exhaustible resource, or from the harvest of a renewable resource, ought to be sold at competitive and affordable relative prices, that reflect the true marginal social cost of production [11, 21, 31].
    3.4. Pollution, in all its forms, should be minimised [32].

4. Given that, within the proposed framework, economic sustainability is unattainable unless we promote economic efficiency and perfect competition, the corresponding institutions should procure the following:
    4.1. Monopoly practices must be avoided. Goods and services produced by many small firms shall be the preferred option.
        4.1.1. This might contribute to a more equitable income distribution, which is often neglected when efficiency criteria are used [21, 36].

4.2. Inflation ought to remain fairly stable [38].

4.3. Regulatory bodies should refrain from abusive market process interventions (e.g. taxes, subsidies, exchange rates, etc.) that may disrupt the desired economic competitive conditions of the market [21, 34].

2.3 Environmental Sustainability

"The environmental interpretation of sustainability focuses on the overall viability and health of living systems - defined in terms of a comprehensive, multiscale, dynamic and hierarchical measure of resilience, vigour and organisation" [21]. Resilience can be interpreted as the ability of a system to return to equilibrium after an external perturbation. Vigour refers to the primary productivity of an environmental system and is analogous to output and growth in economics. Lastly, organisation makes allusion to the complexity and structure of an ecological or biological system [21].

2.3.1 Critical Natural Capital

Regarding human development, what matters about the environment are not particular stocks of natural capital, but the ability of the whole natural capital stock to perform the environmental functions that are essential for human welfare. Therefore, Critical Natural Capital (CNC) is the natural capital responsible for important (or critical) environmental functions and which cannot be substituted in the provision of these functions (e.g. oxygen for breathing). Furthermore, in this context, environmental sustainability may be defined as the maintenance of important environmental functions [52]. In other words, this conception of environmental sustainability concentrates on the capacity of the natural capital stock as a whole to perform critical environmental functions, rather than focusing on particular components of natural capital [53]. Consequently, environmental functions, not necessarily critical, have been identified and classified in many different ways. For example the four categories suggested by [54] and highlighted by [52]:

- "**Regulation functions:** regulation of essential ecological processes and life support systems (e.g. bio-geochemical cycling, climate regulation, water purification, etc.)".
- "**Production functions:** harvesting from natural ecosystems of, for example, food, raw materials and genetic resources".
- "**Habitat functions:** provision by natural ecosystems of refuge and reproduction habitat to wild plants and animals and thereby contribution to the (in situ) conservation of biological and genetic diversity and evolutionary processes".
- "**Information functions:** provision of many possibilities for recreation and aesthetic enjoyment, cultural and historical information, artistic and spiritual inspi-

ration, education and scientific research".

Stocks of environmental capital which are responsible for regulation functions, in the previous classification, are responsible for sustaining and maintaining the stability and resilience of ecosystems, as they support the basic processes and cycles in the internal functioning of natural ecosystems [52].

In general, CNC is only identifiable through particular characteristics which enable it to perform environmental functions of concern. Therefore, the identification of basic characteristics of natural capital (e.g. bedrock characteristics and geological processes, atmospheric properties and climatological processes, hydrological processes and properties, etc.) is the first step towards the determination of which natural capital is critical. Then, assuming that environmental functions which are essential for human welfare (critical environmental functions) were successfully identified, these could be related to certain environmental characteristics and hence related to particular components of natural capital (CNC in this case) [53]. As a result, the association of particular environmental characteristics with natural capital has led to the recognition of four basic categories of natural capital: air, water (fresh and marine), land (soil, space and landscape) and habitats (ecosystems) [53]. Similarly, as suggested by [53], environmental functions can be allocated to one or more of these four types of natural capital, and categorised into:

1. "**Source functions:** refer to the provision of goods for human use and benefit, very often through the economy".
2. "**Sink functions:** refer to the capacity of natural capital to dispose the wastes generated by human activities".
3. "**Human Health and Welfare functions:** refer to other services provided to humans by natural capital, very often of a non-economic kind which maintain health and contribute to human well-being in a variety of ways".
4. "**Life Support functions:** refer to the natural processes which maintain both ecosystems and the biosphere as a whole. These are the functions of and for the natural world overall, as opposed to functions specifically for people. Many of the source, sink and human health and welfare functions depend on life support functions for their continuance".

These types of environmental functions, as a whole, are responsible for making the Earth able to support life and, therefore, these types of environmental functions can be the most relevant for humanity [53].

On one hand, as stated by [52], the identification of environmental functions and the natural capital required for them is an exercise informed by environmental science, but there are still large areas of uncertainty (outcomes are known, but not their probabilities) or even ignorance (unknown outcomes) regarding the causes, effects and dynamics of the environmental functions that sustain ecosystems. It is clear that there is a close relationship between environmental functions and particular components of natural capital, but the relationship is complex and is not one-to-one [53]. Therefore, a single component of natural capital might be required for several, possibly very different, environmental functions at the local, regional or even global scale [52, 53]. On the other hand, the perception and valuation of the relevance of particular environmental functions for human welfare is a subjective matter. Consequently, [52] suggests great caution in categorising environmental functions (and, therefore, elements of natural capital) as 'non-critical' because of the unknown consequences.

As it was previously mentioned, environmental functions are not necessarily performed by unique particular stocks of natural capital. Consequently, there might be acceptable substitutes for certain environmental functions. Similarly, not all environmental functions need to be preserved, as not all are essential for human welfare (economic, health-related and other forms of welfare). Unfortunately, there is considerable uncertainty about which environmental functions are important (or critical) for human welfare and why, especially regarding regulation and habitat functions which are believed to sustain life processes. In other words, with the present state of knowledge about ecosystems and environmental functions, it remains uncertain which environmental functions, and therefore which stocks of environmental capital, are critical and which are not [52].

2.3.2 Environmental Sustainability in Practice

Following the complexity and uncertainty associated with the identification of critical environmental functions and CNC, the environmental sustainability concept has also been presented in the form of principles, such as those proposed by [55, 56]:

1. Limit the human standard of living to that which does not exceed the carrying capacity of the planet.

2. Increase the efficiency of technology, infrastructure services and lifestyle, and do not increase human throughput.

3. Natural regeneration rates of renewable resources should not be exceeded by harvesting rates and waste emissions from the harvest of renewable resources must not surpass the assimilative capacity of the receiving environment.

4. The exploitation of exhaustible resources should not exceed the rate at which renewable substitutes are created.

Nevertheless, in the view of [52, 53], it is more convenient to express the concept of environmental sustainability in terms of the most severe environmental problems of today, considering insights from environmental science. As a result, previous environmental sustainability principles have been reformulated into seven sustainability principles which are intended to ensure the preservation of critical environmental functions [52]:

1. **Prevent Global Warming and Ozone Depletion:** “anthropogenic destabilisation of global environmental processes, such as climate patterns or the ozone layer, must be prevented. Most important in this category are the maintenance of biodiversity, the prevention of climate change by the stabilisation of the atmospheric concentration of greenhouse gases, and safeguarding the ozone layer by ceasing the emission of ozone depleting substances”.

2. **Maintain Biodiversity:** “critical ecosystems and ecological features must be absolutely protected to maintain biological diversity (especially of species and ecosystems). Criticality in this context comes from a recognition not only of the perhaps as yet unappreciated use value of individual species, but also of the fact that biodiversity underpins the productivity and resilience of ecosystems. Resilience depends on the functional diversity of the system. This depends in turn, in complex ways, not just on the diversity of species but on their mix and population and the relations between the ecosystems that contain them”.

3. **Renew Renewable Resources:** “the renewal of renewable resources must be fostered through the maintenance of soil fertility, hydrobiological cycles and necessary vegetative cover, and the rigorous enforcement of sustainable harvesting. The latter implies basing harvesting rates on the most conservative estimates of stock levels, for such resources as fish; ensuring that replanting becomes an essential part of such activities as forestry; and using technologies for cultivation

and harvest that do not degrade the relevant ecosystem and deplete neither soil nor genetic diversity".

4. **Use Non-Renewables Prudently:** "depletion of non-renewable resources should seek to balance the maintenance of a minimum life expectancy of the resource with the development of substitutes for it. On reaching the minimum life expectancy, its maintenance would mean that consumption of the resource would have to be matched by new discoveries of it. To help finance research for alternatives and the eventual transition to renewable substitutes, all depletion of non-renewable resources should entail a contribution to a capital fund. Designing for resource efficiency and durability can ensure that the practice of repair, reconditioning, re-use and recycling approach the limits of their environmental efficiency".

5. **Respect Critical Loads for Ecosystems and Standards for Human Health:** "emissions into air, soil and water must not exceed their critical load, that is the capability of the receiving media to disperse, absorb, neutralise and recycle them, without disturbing other functions, nor may they lead to life-damaging concentrations of toxins. Synergies between pollutants can make critical loads very much more difficult to determine. Such uncertainties should result in a precautionary approach in the adoption of safe minimum standards". As suggested by [57], it is more practical to define safe minimum standards in terms of conservation practices.

6. **Conserve landscape/amenity:** "landscapes of special human or ecological significance, because of their rarity, aesthetic quality or cultural or spiritual associations, should be preserved".

7. **Apply the Precautionary Principle:** "risks of life-damaging events from human activity must be kept at very low levels. Technologies that threaten to cause serious and long-lasting damage to ecosystems or human health, at whatever level of risk, should be foregone".

Similarly, based on an expert survey (See [58]), [53] listed the most important environmental themes and indicators of our time, and allocated these to a basic category of natural capital as shown in Table 2.1.

Table 2.1: Most important environmental themes of our time, according to a panel of 2300 European environment experts surveyed by Eurostat [58], related to a basic category of natural capital [53].

Type of Natural Capital	**Principal Environmental Theme/Indicator**
Air/Atmosphere	1. Air pollution, resulting in climate change, ozone depletion and effects on ecosystems and human health.
Water	1. Availability of water resources. 2. Water pollution.
Land (soil/space/landscape)	1. Loss of soil fertility/land degradation. 2. Depletion of non-renewable resources 3. Land pollution/solid waste disposal. 4. Landscape degradation.
Habitats	1. Habitat and species loss. 2. Depletion of renewable resources (e.g. fish, forests).

According to [52, 53], the application of the previously listed sustainability principles and the consideration of Table 2.1, permits critical environmental functions, and the critical natural capital which is required for them, to be tentatively (because of uncertainties) identified (See [52, 53] for further details). Therefore, although there is a need to develop further understanding of environmental criticality, all the previously provided guidance in the approach of today's most severe environmental problems will need to be supplemented as new environmental problems become part of the global agenda.

2.4 Social Sustainability

No consensus seems to exist regarding what criteria should be used in defining social sustainability. Therefore, social sustainability is commonly considered to be the least developed pillar of sustainable development [59]. Nonetheless, common to most existing definitions of social sustainability, derived by discipline-specific authors or policy makers, is the preservation of essential social capital for future generations and the maintenance of resilience, vigour and organisation of social and cultural systems [21, 59]. In other words, social sustainability is not about meeting all human needs or flourishing human life, but about sustaining the basic conditions necessary for socio-cultural systems to not systematically degrade [59].

On one hand, the concept of social sustainability resembles the principles of environmental sustainability, but in this case applied to a human socio-cultural system. Social sustainability is about reducing the vulnerability, maintaining the health (resilience, vigour and organisation) and preserving the ability of social and cultural systems to withstand shocks [21]. On the other hand, the creation and preservation of social capital are goals shared by the concepts of social cohesion and social sustainability. Nevertheless, social sustainability does not claim to maximise individual or overall social welfare. Social sustainability focuses on the preservation, more than on the creation, of essential social capital for future generations. In other words, social sustainability intends to at least ensure an intergenerationally equitable quality of life [60].

2.4.1 Social Development, Social Welfare and the Concept of Quality of Life

In general, the concept of social development makes reference to improvements in both individual well-being and the overall social welfare that result from an increased capacity of individuals and groups of people to work together to achieve common objectives [21]. Moreover, as mentioned in Section 2.1, a few decades ago the notion of individual well-being and social welfare was directly associated with material wealth and rates of economic growth. Later on, the conception of individual well-being and social welfare would now include non-material and qualitative aspects of development. In consequence, quality of life became the main welfare goal of social development [60].

First introduced in the 1960s, the concept of quality of life considers two major dimensions - objective living conditions and subjective well-being. Objective living conditions include measurable living circumstances (e.g. living standards, working conditions and state of health). In contrast, the notion of subjective well-being is not measurable and relies on the perception, evaluation and appreciation of life and living conditions by individuals [61]. In addition, regardless of its measurability, based on a society's level of development, an individual member of society aspires to different levels of need regarding [62]:

- **Way of life:** e.g. how they live, work and play.
- **Culture:** e.g. shared beliefs, customs and values.
- **Community:** e.g. stability, cohesion and services.
- **Political systems:** e.g. participation in decisions.
- **Environment:** e.g. quality and availability of natural resources.
- **Health and well-being.**
- **Personal and property rights:** e.g. human rights.
- **Fears and aspirations:** e.g. perception of safety and future.

In this regard, equity and poverty alleviation are social priorities. Consequently, social goals include strategies to reduce vulnerability, improve equity and ensure that basic needs are met [21].

2.4.2 Social Capital

“The social capital of a society includes the institutions, the relationships, the attitudes and values that govern interactions among people and contribute to economic and social development” [63]. Moreover, given that it is a relational concept, social capital cannot be regarded as an individual characteristic, it only exists if it is shared by several individuals. In other words, social capital is not just the sum of the institutions (formal laws) that underpin society, it also includes human capital and cultural capital [21, 60]. On one hand, in this context, human capital makes allusion to human health, education/knowledge, skills/employment, freedom, diversity[2], security, mobility and access to the resources/services needed for a decent standard of living [21, 59]. On the other hand, cultural capital makes reference to “the shared values and rules for social conduct expressed in personal relationships, trust and a common sense of ‘civic’

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[2] In human social systems, diversity can be interpreted as diversity of personalities, ages, genders, skills, etc. [59].

responsibility, that makes society more than a collection of individuals" [21, 60, 63]. Finally, apart from obvious cases like health and well-being, the determination of which elements of social capital are essential, and which are not, seems to be a subjective matter.

2.5 Energy for Sustainable Development

Energy is fundamental for human development since it has a direct impact on the three dimensions of human well-being. At first, by the late 1990s, it was internationally agreed that universal access and adequate availability of energy was central to attain economic growth and social improvement, as it enhanced quality of life and satisfied basic human needs as: cooking, heating, cooling, lighting, etc. [11, 25]. Later, with the arrival of the 2000s, our dependence on energy increased significantly as the concept of "basic human needs" would now also include the usage of energy for the operation of electrical appliances and information and communication technologies, in many occasions with recreational purposes. Similarly, all sectors of the economies of every country became heavily dependent on machinery [14, 64]. At the same time, we noticed that energy could also be beneficial for environmental protection, and therefore for human development, for example by reducing deforestation [1]. Unfortunately, with the excessive usage of fossil fuels as primary energy sources, global warming and climate change became part of the global agenda. Thus, we realised that in order to achieve the goals of sustainable development, an environmental, social and economically sustainable transformation of energy was essential [6, 7]. In fact, the sustainable transformation and efficient use of energy would become one of the most important challenges of our time and it would turn into one of the 17 SDGs in 2015 [15].

Over the last four decades, our reliance on electrical energy has increased significantly and it is expected to increase further due to foreseen changes in the transport sector. In addition, as it was mentioned previously, fossil fuels are loosing attractiveness, as a source of energy, due to emissions regulations and the socio-political relevance of climate change [64]. Consequently, in order to move towards sustainable development, it is necessary to ensure universal access to affordable, reliable and modern energy services that could reduce the environmental impacts of the energy sector and allow the economies to maintain their productive capacities. Nevertheless, although nuclear energy technologies are net zero carbon and could improve current energy systems, some countries (e.g. Germany) have decided not to retain nuclear energy technology and other countries (e.g. Croatia) are yet to decide on nuclear energy mainly due to: cost, public perception, politics or imposed market distortions [14, 65].

2.6 Chapter Summary

From Development to Sustainable Development

- On one hand, development is the satisfaction of human needs and aspirations which can be allocated to one of the three interdependent and mutually reinforcing pillars of human well-being - economic development, social development and environmental protection. On the other hand, sustainable development is the uninterrupted satisfaction of human needs and aspirations over time or for a significantly long period of time considering a human life time scale.

- Due to the interlinkages between them, it seems impossible to improve a particular pillar of sustainability without having consequences elsewhere. Therefore, sustainable development is about the best trade-offs between different sustainability aspects.

- As of today, hundreds of indicator sets have been proposed to measure our progress towards achieving sustainable development. Nonetheless, appropriate indicators of sustainable development are not independent of their object of study. In addition, indicators of sustainable development depend on time and location due to the fact that human needs and aspirations are socially and culturally determined.

Economic Sustainability

- There are two opposing models of economic sustainability: weak and strong sustainability. Although both pursue the ultimate objective of promoting constant levels of consumption per capita for future generations, the two models have contrasting opinions regarding the role of natural resources.

- On one hand, the weak sustainability model aims to achieve and maintain constant consumption per capita while preserving the economy's productive capacity (total stock of assets). On the other hand, the strong sustainability model also pursues constant consumption per capita, but focuses only on the maintenance of the stock of natural capital rather than in the conservation of the total stock of assets.

- Misinterpretation of the strong sustainability model leads to the belief that strong sustainability is about the preservation of every single natural asset. Nevertheless, sustainable development requires the maintenance of natural assets above a critical level, rather than the preservation of the environment as it is.

- The weak sustainability model can be modified to minimise the usage of non-renewables and, therefore, it can be modified to include the essence of strong sustainability. As a consequence, a secondary finding of this study, it was found that the weak sustainability model is the economic sustainability model that most resembles the foundations of sustainable development and provides an economic sustainability framework that can be enriched to include the essence of strong sustainability and important considerations that are disregarded by both models.

- Assuming that a regulated consumption of exhaustible resources is allowed, a constant consumption (per capita) path is achievable upon utilisation of Hotelling's rule for a socially optimal rate of extraction of exhaustible resources and Hartwick's rule which provides the necessary investment policy to achieve a constant consumption per capita.

    - **Unique Contribution:** As a secondary finding, Hotelling's rule was found to be commonly misunderstood as: "the socially optimal rate of extraction of any non-renewable resource is such that its **price** increases at a rate equal to the interest rate" [43], which is only true in a particular case. In reality, Hotelling's rule establishes that the socially optimal rate of extraction of any non-renewable resources is such that its **return (price minus cost)** increases at a rate equal to the market interest rate.

- **Unique Contribution:** Not only the strong, but also the weak economic sustainability model assumes a state of general equilibrium, which rarely exists in the real world. Similarly, both models disregard pollution in all its forms. Consequently, an original modern definition of economic sustainability, based on an enriched version of the weak sustainability model, is provided at the end of this chapter.

Environmental Sustainability

- Environmental sustainability is the preservation of the ability of the whole natural capital stock to perform the environmental functions which are essential for human welfare (e.g. climate regulation, water purification, etc.). In this context, Critical Natural Capital (CNC) is the natural capital responsible for critical environmental functions and which cannot be substituted in the provision of these functions. Therefore, environmental sustainability can also be understood as the conservation of essential natural functions and, by extension, of critical natural capital if applicable.

- The relationship between essential environmental functions and particular components of natural capital is complex and is not one-to-one. A single element of natural capital might be necessary for several, potentially very different, environmental functions at the local, regional or global scale.
- Following the uncertainty regarding the causes, effects and dynamics of environmental functions, environmental sustainability has been presented in the form of principles and in terms of the most severe environmental problems of today. In other words, in practice, environmental sustainability is the combat of today's most severe environmental problems, which will have to be updated as new environmental problems become part of the global agenda.

Social Sustainability

- No consensus seems to exist regarding what criteria should be used in defining social sustainability. However, common to most existing definitions is the preservation of essential social capital. This is, social sustainability is about sustaining the basic conditions (quality of life) necessary for socio-cultural systems to not systematically degrade.
- The social capital of a society includes not only the institutions (formal laws) that underpin society, but also human capital and cultural capital.
- No agreed criteria for the identification of essential social capital was found during this study.

Energy for Sustainable Development

- Universal access and adequate availability of energy is fundamental to attain economic growth and social improvement. Not only it satisfies basic human needs (e.g. heating, lighting, information and communication technologies, etc.), but also all the economies around the world are heavily dependant on machinery. Similarly, our reliance on electricity is expected to keep increasing due to foreseen changes in the transport sector.

- Although energy products and services may be beneficial for environmental protection (e.g. by reducing deforestation), the excessive utilisation of fossil fuels has been degrading the environment by contributing to global warming and climate change. Thus, in 2015, the sustainable transformation and efficient use of energy was recognised by the United Nations General Assembly as one of the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development.

- Universal access to affordable, reliable and modern energy services that could reduce the environmental impacts of the energy sector, without diminishing the economies productive capacities, is now essential for a sustainable future. Consequently, in the pursuit of sustainable development, we cannot afford to disregard innovative energy systems like nuclear energy technologies that some countries (e.g. Austria) have excluded due to public perception, politics or imposed market distortions.

Chapter 3

SUSTAINABLE ENERGY SUPPLY INDICATORS

In order to assess the sustainability of energy supply technologies, like the SMRs, a relevant set of 40 sustainable energy supply indicators was developed, in accordance with the foundations of sustainable development (See Sections 2.1, 2.2), current Sustainable Development Goals [15, 31] and mostly based on previous indicator frameworks developed for sustainability assessments of energy supply technologies (See Section 3.1). A core set of 30 indicators was allocated to the three pillars of sustainable development and an extra set of 10 indicators was introduced in order for investors to evaluate the attractiveness of investing in energy supply technologies (See Table 3.1 for the complete list of indicators and Sections 3.2 - 3.5 for the corresponding descriptions). Although it is not a sufficient condition and it might be interpreted as corporate sustainability, the attractiveness of investing in energy supply technologies was recognised as a necessary condition for a sustainable energy future. Without investment, sustainable energy supply systems cannot be developed and deployed.

On one hand, it is acknowledged that the selection and allocation of sustainable energy supply indicators to the three dimensions of sustainable development requires personal judgements and some elements of arbitrariness. Consequently, although they were considered, some impact areas were neglected as they were found to be: difficult to measure[3] or redundant[4]. On the other hand, sustainability evaluations rely on the score as much as on the weight of the indicators used. Throughout this study equal weights have been given to each indicator within their corresponding category and, therefore, the conclusions presented in further Chapters are only valid within the stated weights.

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[3] Fair income distribution, energy-related depletion of renewable resources and visual amenity.

[4] Maturity of technology and experience with construction schedules.

Table 3.1: Sustainable Energy Supply Indicators.

Category	**Issue Addressed**	**Indicator**	**Measurement Unit**
Attractiveness of Investment	Financial Figures of Merit	Size of Investment	(£) or (£/MWe)
		Net Present Value (NPV)	(£) or (£/MWe)
		Internal Rate of Return (IRR)	(%/100) or (%)
		Return on Investment (ROI)	(%/100) or (%)
		Payback Period	(yr)
		Economic Dispatchability (ED)	(%/100) or (%)
	Risk of Investment	Maturity of Technology	(‘mature’ or ‘not mature’)
		Corruption Perception Index (CPI)	(0-100)
		Long-Term Sovereign Credit Rating, Local Currency	AAA, AA, A, BBB, BB, B, CCC, CC, C, R, D, SD or NR
		Long-Term Sovereign Credit Rating, Foreign Currency	AAA, AA, A, BBB, BB, B, CCC, CC, C, R, D, SD or NR
Techno-Economic	Affordability of Energy Services	Levelised Cost of Electricity (LCOE)	(p/kWh)
		Fuel Price Sensitivity Factor (FPSF)	(%/100)
	Reliability and State of Technology	Capacity Factor	(%)
		Availability Factor	(%)
		Average Ramp Rate	(% of P_{max}/min)
		Average Response Time	(min) or (h)
		Reserves-to-Production (R-P) Ratio	(yr)
Environmental	Climate Change	Global Warming Potential (GWP)	($kg\ CO_2$ equiv/kWh)
	Ozone Depletion	Ozone Depleting Potential (ODP)	($kg\ CFC-11$ equiv/kWh)
	Effects on Ecosystems and Human Health Caused by Air Pollution	Photochemical Ozone Creation Potential (POCP)	($kg\ C_2H_4$ equiv/kWh)
	Water Eco-toxicity	Freshwater Eco-toxicity Potential (FWETP)	(kg 1,4-DCB equiv/kWh)
		Marine Eco-toxicity Potential (METP)	(kg 1,4-DCB equiv/kWh)

Continued on next page

Table 3.1 – Continued from previous page.

Category	**Issue Addressed**	**Indicator**	**Measurement Unit**
	Acidification	Acidification Potential (AP)	($kg\ SO_2$ equiv/kWh)
	Eutrophication	Eutrophication Potential (EP)	($kg\ PO_4^{3-}$ equiv/kWh)
	Land Use	Land Occupation	($m^2\ yr$ equiv/kWh)
	Land Degradation	Greenfield Land Use	(%)
	Loss of Soil Fertility	Terrestrial Eco-Toxicity Potential (TETP)	(kg 1,4-DCB equiv/kWh)
	Solid Waste	Non-Radioactive Waste	(kg/kWh)
		Radioactive Waste	(m^3/kWh)
	Depletion of Non-Renewable Non-Energetic Resources	Usage of Non-Renewable Non-Energetic Resources	($kg\ Sb$ equiv/kWh)
Social	Access to Essential Services	Flexibility	(0-40)
	Skills/Employment	Total Employment	(person-yr/GWh)
	Local Community Impact	Proportion of Staff Hired from Local Community	(%)
	Human Health	Human Toxicity Potential (HTP)	(kg 1,4-DCB equiv/kWh)
		Human Health Impacts from Radiation	(DALY/GWh)
	Human Security	Risk of Severe Accident	(fatalities/GWh)
		Maximum Credible Number of Fatalities per Accident	(fatalities)
		Nuclear Proliferation	(0-3)
	Energy Security	Fuel Energy Density	(GJ/m^3)
	Intergenerational Equity	Critical Waste Confinement Time	(1000 yrs)

3.1 Measuring Sustainable Energy Supply

As mentioned in Subsection 2.1.1, international and national organisations have constructed many criteria and indicators relevant to sustainable development. However, in general, the sets of indicators developed by international organisations are not suitable for sustainability assessments of energy supply technologies because they are meant to be used at the national level and, therefore, they are not technology specific [66]. In other words, no set of indicators is relevant for all applications. The selection of indicators is determined by the target audience, scope and focus of the corresponding assessments. This is, policy makers and corporate managers require different sets of indicators [67]. As a result, some of the existing indicator frameworks are limited to measure corporate sustainability while others go beyond financial figures of merit [64].

3.1.1 Characteristics of Sustainable Energy Supply Indicators

On one hand, quantification is an aspect of sustainable energy supply indicators that deserves special attention. Ideally, it should be possible to express these indicators as a numerical value. However, previous works have noted that the social dimension of sustainability is often not fully expressible in a quantitative manner [67]. Therefore, in most cases, indicators of social sustainability are highly subjective, while economic and environmental indicators are well developed [66]. On the other hand, another important requirement of sustainable energy supply indicators is the the availability of data. Indicators for the assessment of energy supply systems should be accessible to analysts through existing statistics or through data that can be collected reasonably easily. Furthermore, according to [67], the desirable characteristics of sustainable energy supply indicators are those listed below:

Scientific

1. "**Measurable and quantifiable:** adequately reflect the phenomenon intended to be measured".

2. "**Meaningful:** appropriate to the need of the user".

3. "**Clear in value:** distinct indication of which direction is good and which is bad".

4. "**Clear in content:** measured in understandable units that make sense".

5. "**Appropriate in scale:** not over or under aggregated".

6. “**No redundancy or double counting:** indicators are not overlapping in what they measure”.
7. “**Robust and reproducible:** indicator measurement is methodologically sound, fits the intended purpose and is repeatable”.
8. “**Sensitive and specific:** indicators must be sensitive to changes in the system under study and, ideally, respond relatively quickly and noticeably”.
9. “**Verifiable:** external persons or groups should be able to verify an indicator”.
10. “**Hierarchical:** to allow a user to understand the level of detail necessary”.

Functional

11. “**Relevant:** for all stakeholders involved”.
12. “**Compelling:** interesting, exciting and suggestive of effective action”.
13. “**Leading:** so that they can provide information to act on”.
14. “**Possible to influence:** indicators must measure parameters that are possible to be changed”.
15. “**Comparable:** if the same indicators are used in several systems, they should provide usable results”.
16. “**Comprehensive:** the indicator set should sufficiently describe all essential aspects of the system under study”.

Pragmatic

17. “**Manageable:** not too many to handle; also important in view of interactions with users and stakeholders”.
18. “**Understandable:** possible to be understood by stakeholders”.
19. “**Feasible:** measurable at reasonable effort and cost”.
20. “**Timely:** reasonably easy to collect and compile without long delays”.
21. “**Coverage of the different aspects of sustainability:** indicators address economic, environmental and social dimensions”.
22. “**Allowing international comparison:** to the extent necessary, in accordance with specific study objectives”.

3.1.2 Previous Criteria and Indicators of Sustainable Energy Supply

Previous criteria and indicators, proposed by international and national organisations, for sustainability assessments of energy supply systems have received various degrees of validation by analysts and other stakeholders. However, [1, 64, 66] are among the most representative and robust evaluation criteria and indicators of the sustainability of energy systems. Common to all these works is a 'cradle-to-grave' approach and the consideration of the multi-dimensionality of sustainable development. Similarly, they all conclude that sustainable development is about the best trade-offs and, therefore, there is no unique best energy supply technology.

First, in 2004, [66] published a framework for a comparative evaluation of the sustainability of energy supply systems, under German conditions. Based on diverse bottom-up methodologies, [66] constructed a set of 18 technology specific and quantitative indicators, considering the three pillars of sustainable development. For the previous, Life Cycle Assessment (LCA), Risk Assessment (RA) and Impact Pathway Approach (IPA) were some of the methods used by [66]. These methods consider full energy chains (e.g. extraction, conversion, energy generation and waste management). Similarly, the respective indicators were aggregated by estimating total costs and Multi-Criteria Decision Analysis (MCDA). As a result, [66] found that nuclear power is superior to other implemented technologies in terms of total costs, but it is clear that no energy system shows superiority on the basis of all criteria. According to [66], placing emphasis on economy reduces the attractiveness of renewables, placing emphasis on the environment condemns fossil fuelled systems, and the prioritisation of social aspects has a negative impact on nuclear energy.

Second, with the intention to ensure the availability of nuclear energy in a sustainable manner, the International Project of Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched, by the International Atomic Energy Agency (IAEA), in the year 2000. As a result, in 2008, the IAEA published the INPRO methodology for the sustainability evaluation of nuclear energy systems, with a "cradle to grave" approach. Moreover, given that the methodology was developed before the UN adopted back the three pillars of sustainable development scheme, the INPRO methodology is aligned with the three dimensions of sustainable development and with a fourth consideration, institutional infrastructure. The INPRO methodology [1] aims to determine whether or not a given nuclear energy system is sustainable by considering the following subject areas:

1. Economics.
2. Institutional Infrastructure.
3. Waste Management.
4. Proliferation Resistance.
5. Physical Protection.
6. Environment.
7. Safety of Nuclear Reactors.
8. Safety of Nuclear Fuel Cycle.

Furthermore, the INPRO methodology comprises a set of indicators with acceptance limits, covering all the previously listed areas.

Lastly, in 2006, the SPRIng research consortium was formed in the UK with “the main objective of considering the potential role of nuclear power in contributing towards a future sustainable energy system in the UK” [10]. Led by the University of Manchester, the SPRIng consortium partnered with UK’s academia, industry, government and non-governmental organisations, in order to develop a conceptual framework for sustainable development indicators suitable for electricity generation technologies. As a result, the SPRIng sustainability indicators [64], published in 2011, address key techno-economic, environmental and social issues. The set of 43 indicators covers the whole life cycle of electricity and it was developed following a life cycle approach.

3.2 Attractiveness of Investment

As mentioned in Section 2.5, modern human needs cannot be fulfilled without universal access and adequate availability of energy. In relation, if energy related products and services are to be available, energy supply systems need to be developed and deployed. At the same time, the development and deployment of energy supply systems requires investment [68]. Therefore, according to [11], in a world characterised by globalisation and liberalisation of markets, a sustainable energy future is attainable through a combination of measures to achieve economic efficiency and to direct market actors towards energy investments. In other words, the investment in sustainable energy supply systems has to be sufficiently attractive to justify doing so, as our progress towards sustainable development, among other things, depends on the willingness of market actors to invest in sustainable energy technologies.

3.2.1 Financial Figures of Merit

From an economics point of view, the attractiveness of investing in energy supply technologies is assessed by evaluating financial figures of merit such as those presented below. Although these are the most commonly used to assess the attractiveness of an investment, these are not all the financial indicators that can be used and it is up to the corresponding evaluator to determine what financial figures of merit to use as evaluation parameters.

3.2.1.1 Size of investment

Total investment required to construct and commission a power plant (e.g. overnight capital cost and the accrued interest during construction and commissioning periods) (See Equation A.1 in Appendix A.1). An acceptable size of investment will depend on available resources of investment, the overall state of the economy of a given region/country, and other factors. Similarly, the affordability of the investment will vary with time and location. On one hand, for a given firm of the private sector, the limit of investment depends on its total income and profit. On the other hand, in the case of governments, the limit of investment is defined by the available budget. Consequently, in the case of governments, the affordability of an investment can be determined from a review of the historical investments in the region/country of interest [68].

3.2.1.2 Net Present Value (NPV)

The difference between income and expenses is known as ‘net benefit or net income’. In relation, the net income is time dependent and, in order to consider the time value of money, should be discounted using an appropriate discount rate r (See Table 3.2). Therefore, the NPV of a project is equivalent to the cumulative discounted net benefit of the project (See Equation A.2 in Appendix A.2) [68].

Table 3.2: Rule of thumb, real discount rates, depending on the market scenario [68].

Scenario	**Discount rate (%)**
Government owned utility in a regulated market	3 - 5
Private sector utility in a regulated market	5 - 10
Private sector utility in a deregulated market	10 - 15

3.2.1.3 Internal Rate of Return (IRR)

Sometimes referred to as “discounted rate of return”, the IRR is an iterative method that determines the discount rate that is needed to balance the stream of expenditures and income (See Equation A.3 in Appendix A.3). Therefore, the IRR is the minimum acceptable rate of return of a project [68]. In general, “the higher a project's internal rate of return, the more desirable it is to undertake” [69].

3.2.1.4 Return on Investment (ROI)

Average profit accumulated over a set period of time, usually average annual profit, expressed as a percentage of the cost of the project (aka rate of return). Therefore, the higher the ROI the higher the attractiveness of an investment. Nonetheless, it is important to mention that, the ROI is not sensitive to discount rates as this parameter is not levelised (See Equation A.4 in Appendix A.4) [68, 70].

3.2.1.5 Payback Period

Time required to recover the cost of an investment (See Equation A.5 in Appendix A.5). Furthermore, long payback periods are not desirable for investment positions. However, as in the case of the ROI method, the payback period does not consider the time value of money [68, 71].

3.2.1.6 Economic Dispatchability (ED)

Economic drawback of load-following energy generation schedules. For a given energy supply technology, this indicator is expressed as the capital cost share of the Levelised Cost of Electricity (LCOE) (See Equation A.6 in Appendix A.6) [64].

3.2.2 Risk of Investment

The attractiveness of investing in a certain project, e.g. energy supply technologies, is not only measured using financial figures of merit, but also by estimating the risk associated with the investment. In relation, due to the risk associated, usually large scale power plant projects are only undertaken with the support of national governments [68]. Therefore, the risk of investing in energy supply technologies must be evaluated with the support of relevant indicators (e.g. maturity of technology, corruption perception index, and long-term sovereign credit ratings) in order for investors to decide whether to proceed or not with investments of this nature. As a whole, the indicators presented in the previous Subsection (Subsection 3.2.1) and those discussed in this Subsection will reflect the investment climate and requirements of a given country [68].

3.2.2.1 Maturity of Technology

Technical maturity, which is strongly linked with regulatory uncertainties, represents an investment risk. In relation, it is assumed that the financial risk of investing in energy supply technologies is diminished if the technology in question is mature or proven [68]. Moreover, power plants/energy supply technologies can be considered to be mature if similar power plants have already been licensed and operated, in the country of interest. Similarly, for those countries intending to deploy a particular energy supply technology for the first time, the maturity criterion could be if the technology of interest has been licensed and operated in the country of origin [68]. Lastly, this indicator is not quantitative and, therefore, it only takes the values of 'mature' or 'not mature' (See Table A.1 in Appendix A.7).

3.2.2.2 Corruption Perception Index (CPI)

As noted by [64], violations of human rights and corruption are a major investment risk in countries where the social and regulatory regimes are lax. Nonetheless, due to personal value judgments and the lack of evidence of violations of human rights and corruption, it is difficult to assess corruption in an unbiased fashion. Therefore, in order to measure the level of corruption of a particular country, [64] suggests the usage of the Corruption Perception Index (Corruption Perception Index (CPI)) developed by Transparency International [72]. Based on the level of corruption of the corresponding politicians and official administrators, the CPI scores countries on a scale from 0 to 100, where 0 means extremely corrupt and 100 means not corrupt at all.

3.2.2.3 Long-Term Sovereign Credit Ratings (Foreign and Local Currency)

Credit ratings, among other tools, can be used by investors when making decisions about purchasing bonds and other fixed income investments [73]. In particular, a sovereign credit rating is the credit rating of a country or sovereign entity. Sovereign credit ratings reflect the level of risk associated with investing in a particular country as these ratings consider: political risk, institutional and governance effectiveness, economic structure and growth prospects, external finances, and fiscal and monetary flexibility of a given country [74]. Therefore, a solid sovereign rating from one of the largest credit rating agencies (e.g. Standard & Poor's, Moody's, and Fitch) demonstrates a country's capacity to meet its financial commitments and its likelihood to attract foreign investment [74].

Usually, a good sovereign credit rating is essential for developing countries in order to access funding in international bond markets and/or to attract foreign direct investment [74]. Additionally, credit rating agencies make a distinction between foreign currency and local currency ratings, in order to communicate an issuer's capacity to meet its obligations denominated in its local currency or in foreign currency [75]. As a result, given the difficulty to measure the political stability of a given country and following Prof. Timothy Abram's suggestion, I recommend the usage of long-term sovereign credit ratings - in foreign or local currency, depending on the case - as a direct measure of the risk of investing in a particular country and as an indirect measure of the political stability of the country in question. Lastly, it is recognised that different credit rating agencies might assign different credit ratings to a particular country. However, it has been assumed here that the credit ratings assigned by the largest credit rating agencies, to a particular country, will not be significantly different. Therefore, following the previous assumption, Standard & Poor's metrics [75] and ratings [76, 77] can be safely used to measure these two indicators (See Table A.2 in Appendix A.8).

3.3 Techno-Economic Indicators

As recognised by the United Nations (UN), in the 2030 Agenda for Sustainable Development [31], access to affordable, reliable and modern energy services is fundamental for a sustainable development. Therefore, when assessing the techno-economic sustainability of an energy supply technology, affordability, reliability and state of technology are precisely the issues to be addressed and measured by techno-economic indicators as those presented below. In relation, for energy services to be affordable, the cost of energy (e.g. electricity) supplied by a power plant has to, at least, be comparable with the production costs of alternative energy supply options, in the same time frame and geographical location [68]. Similarly, in order to be reliable, energy supply technologies must promote energy security and offer the technological properties that are required for the smooth operation of electrical grids.

3.3.1 Affordability of Energy Services

3.3.1.1 Levelised Cost of Electricity (LCOE)

Lifetime discounted cost of owning and operating a power plant, expressed in cost per unit electricity generated (See Equation B.1 in Appendix B.1) [78]. In other words, taking into account an appropriate discount rate, the LCOE represents the average price of electricity that consumers would have to pay for the investor to break even and repay all the costs incurred by owning and operating a power plant through the lifetime of the power plant (e.g. capital costs, operation and maintenance costs, fuel costs, carbon taxes and decommissioning costs). In relation, the economics of large scale nuclear power plants are heavily influenced by their capital cost and the applicable discount rate. On one hand, the capital cost of large scale nuclear power plants accounts for approximately 65 - 85% of their LCOE [79]. On the other hand, as shown below in Table 3.3, increasing the discount rate can double the LCOE of large scale nuclear power plants[5].

Table 3.3: LCOE ranges of large scale nuclear energy technologies, reported in 2015. Source: [80].

Discount rate (%)	**LCOE** (p/kWh)
3	1.6-4.1
7	2.3-6.4
10	3.1-8.7

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[5] Originally presented in USD 2013/MWh. The following exchange rate was used: 1 USD = 0.64 GBP [81].

3.3.1.2 Fuel Price Sensitivity Factor (FPSF)

Impact of a doubling in fuel prices on the LCOE. In other words, the FPSF is the scale factor by which the LCOE would have to be multiplied if fuel costs doubled (See Equation B.2 in Appendix B.2) [66, 67]. Therefore, this scale factor reflects the sensitivity of the LCOE to fuel price fluctuations, which is an important factor considering the desired medium and long-term stability of electricity prices [66]. A fuel price sensitivity factor close to one indicates that the LCOE, of a given energy supply technology, is robust against fuel price variations.

The fuel price sensitivity factor varies greatly between energy supply technologies due to the different size of the capital cost and fuel expenditures required for different electricity generation technologies. Coal, gas and large scale nuclear energy supply technologies hold fuel FPSFs of approximately 1.35-1.40, 1.74-1.75 and 1.10-1.15 respectively, assuming a 10% discount rate and neglecting carbon taxes [64, 67]. The difference between the FPSF of gas and the other two energy supply technologies attends to the fact that coal and large scale nuclear energy technologies have significantly higher capital costs than gas energy technologies [64]. Lastly, given that their required 'fuel' is practically free, renewable energy technologies offer stability of generation costs, but their generation is limited by natural factors.

3.3.2 Reliability and State of Technology

3.3.2.1 Capacity Factor

For a given time period, the net capacity factor of an electricity generation unit, is the ratio of net actual generation to net maximum possible generation (See Equation B.5 in Appendix B.3) [82]. Expressed as a percentage, this ratio gives an indicative figure of how much time is a power plant in in-service mode, out of a given time period (e.g. a year), and how much of its nominal electrical capacity is used in reality. In relation, the capacity factor of a particular energy supply technology may vary from one time period to the next as the generation schedule of a power plant is subject to external factors like changes in fuel price or base load requirements [64]. In other words, the capacity factor will vary not only between base load and peak-demand technologies, but also between technologies relying on dispatchable and intermittent power sources. Consequently, a fair cross-technology comparison will compare technologies with similar operational nature [68].

On one hand, in order to contribute in meeting base load demand, base load technologies are expected to operate continuously, almost at their maximum capacity. Coal, gas and large scale nuclear power plants can achieve capacity factors of above 85% [67]. In fact, modern large scale nuclear power plants can operate with annual capacity factors of 85-90%. On the other hand, the capacity factor of power plants relying on intermittent renewable resources depends mainly on local conditions and tends to be low [67]. For example, the capacity factors of wind energy technologies are generally around 25-35% [64].

3.3.2.2 Availability Factor

Fraction of a given active period during which an energy supply technology is available without any outages (See Equation B.6 in Appendix B.4) [82]. The availability factor of a given energy supply technology (or unit) is limited by refuelling shut down periods, maintenance, failures, etc. Thus, the availability factor is a general measure of the reliability of the energy supply to end users [64]. In other words, a high availability factor ensures an uninterrupted availability of electricity supply, from a particular energy supply unit. For example, light water reactors (excluding Canadian Deuterium Uranium (CANDU) reactors) hold theoretical availability factors of around 93% [64].

3.3.2.3 Peak Load Response

Also known as dispatchability [64], this indicator is the technology-specific ability to respond swiftly to large variations in demand [66]. That is, the peak load response is the ability of a generating unit to increase or decrease generation, or to be brought on line or shut down [83]. Furthermore, as highlighted by [64], it is difficult to measure the peak load response of energy supply technologies with a single indicator, as the peak load response of a given technology depends upon several technical attributes: ramp-up rate, ramp-down rate, minimum up time and minimum down time. For example, Open Cycle Gas Turbines (OCGTs) have ramp-up rates of 90-100% of P_{max} per minute and minimum down times of 8-10 min [64]. In contrast, the Westinghouse AP1000 large scale nuclear reactor has a ramp-up rate of 5% of P_{max} per minute [64].

Previous studies (See [66]) aggregate the peak load response into a single indicator, but the aggregation process is not clear. Similarly, [64] suggests that energy technologies must be ranked on each of the four technical attributes of peak load response, previously mentioned, and then the peak load response of a given technology should be derived by summing its four rankings. Nonetheless, if the peak load response of energy supply technologies is presented as an aggregated indicator in relative scales, as in the case of [64, 66], the reader has limited access to important information that could be used for further studies or cross-technology comparisons. In consequence, I suggest that the peak load response of energy supply technologies should not be aggregated into less than two indicators: **average ramp rate** and **average response time**. On one hand, the **average ramp rate** of an energy supply technology is the average of its ramp-up and ramp-down rates and represents the rate at which a power plant can increase or decrease its output (See Equation B.7 in Appendix B.5). On the other hand, the **average response time** of an energy supply technology is the average of its minimum up time and minimum down time, and it represents the average minimum time required by a power plant to change from 'in service' to 'reserve shutdown' state and vice versa (See Equation B.10 in Appendix B.6).

3.3.2.4 Reserves-to-Production (R-P) Ratio

Lifetime of a given exhaustible resource, expressed in years, at current extraction rates (See Equation B.11 in Appendix B.7). The R-P ratio is an estimate of the longevity of fuel reserves, at the regional or global level, assuming that current extraction rates will remain constant over time, neglecting future reserve discoveries and not considering possible improvements in extraction technologies that would increase the size of economically recoverable reserves [64]. Similarly, indirectly, the R-P ratio measures the vulnerability of electricity supply systems to physical interruptions of primary fuel supplies [64, 67]. In relation, as of late 2016-early 2017, the global R-P ratios of fossil fuels and conventional uranium were those shown below in Table 3.4.

Table 3.4: Global R-P ratios of fossil fuels and conventional uranium, as of 2016-2017.

Resource	**R-P Ratio** (*yr*)
Oil [84]	51
Gas [84]	53
Uranium[6] [85, 86]	133
Coal [84]	153

The R-P ratios of fossil fuels are more realistic than the R-P ratios of other energy sources (e.g. conventional uranium) given that the cumulated experience with fossil fuels is greater than that cumulated with any other energy source. However, according to the so-called 'Red Books' [87], the global R-P ratio of conventional uranium has increased at a steady rate for several decades. In fact, compared to 2017 levels, worldwide conventional uranium reserves increased to 8,070,400 tU in 2019, while production decreased to 54,224 tU/yr in the same year [85]. In other words, the global R-P ratio of conventional uranium increased from 133 years in 2017 to 149 years in 2019 [85, 86].

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[6] Reserves: $7,988,600$ tU / Production: $60,025$ tU/yr.

3.4 Environmental Indicators

As discussed in Subsection 2.3.2, our current level of understanding of critical environmental functions is not sufficient to identify critical natural capital with ease and without uncertainty. Nevertheless, we are fully aware of the current most severe environmental issues regarding air/atmosphere, water, land and habitats. Consequently, considering previous relevant sustainability frameworks (e.g. [64], [66] and [67]) and aiming to address the most relevant environmental themes of our time (See Subsection 2.3.2 for further details), a set of indicators was selected to evaluate the environmental sustainability of energy supply technologies. The selected indicators, cover the whole electricity generation chains of energy supply technologies and, except for the indicators related to radioactive and non-radioactive waste, they are estimated according to the CML impact assessment method, which is a Life Cycle Assessment procedure developed by the Institute of Environmental Sciences of Leiden University in The Netherlands (See [88]). Furthermore, in line with the CML impact assessment method, the characterisation factors for these midpoint impact category indicators can be found in the CML-IA database (See [89]). Finally, it is important to mention that, the CML impact assessment method was not specifically developed to rank energy supply technologies and, therefore, in order to allow for cross technology comparison, environmental sustainability indicators for energy supply technologies are usually presented per unit electricity generated.

3.4.1 Air/Atmosphere

3.4.1.1 Global Warming Potential (GWP)

Expressed in terms of carbon dioxide (CO_2)-equivalents, this indicator represents the global environmental impact of global warming, caused by Green House Gas (GHG) emissions (See Equation C.1 in Appendix C.1) [66]. Therefore, indirectly, the GWP indicator expresses the potential of emitted Green House Gas (GHG)s to cause climate change [64]. Furthermore, the GWP of CO_2 is defined as unity and the GWP factors for different GHGs, as those included in the CML-IA database [89], are expressed relative to the GWP of CO_2. At the same time, GWP factors may vary, depending on the time horizon considered for the assessment of the global warming effect. On one hand, the short term effects of GHGs are best represented by GWP factors which consider short time horizons (20 and 50 years). On the other hand, the cumulative impact of GHGs on global climate is addressed by GWP factors with long time horizons (100 and

500 years). In relation, GWP factors derived considering a time horizon of 100 years (GWP100) are the most widely used and, therefore, they are recommended within this framework [64].

As recognised by the European Parliament [50], the average global temperature is expected to increase by 1.1$°C$ - 6.4$°C$, during this century, if additional emission reduction policies are not implemented. Similarly, the risk of irreversible and potentially catastrophic events would increase significantly if the average global temperature rises by more than 2$°C$ [50]. In consequence, following the adoption of the Paris Agreement in 2015 [90], nations worldwide agreed to limit the average global temperature rise well below 2$°C$. This is why the low carbon emissions of nuclear power and renewables make these technologies environmentally attractive (See Table 3.5).

Table 3.5: Total GWP of multiple energy supply technologies.

Energy Technology	**Total GWP** ($g\ CO_2/kWh$)
Nuclear [64]	5-10
Hydro [91]	4-14
Offshore Wind [64]	5-15
Solar PV [92, 93, 94]	20-40
Biomass [95]	16-74
Pulverised Coal [64]	900-1500

3.4.1.2 Ozone Depleting Potential (ODP)

Expressed relative to the Ozone Depleting Potential (ODP) of $CFC-11$, this indicator quantifies the capacity of Ozone Depleting Substances (ODS) - e.g. Chlorofluorocarbons (CFCs) and other halogenated hydrocarbons - to deplete the ozone layer (See Equation C.2 in Appendix C.2). For example, large scale nuclear power emits approximately 0.55 $\mu g\ CFC-11$ equiv$/kWh$, most of which is emitted during the mining and milling stages, although emissions of CFCs and other halogenated hydrocarbons depend heavily on the enrichment technology used [64]. Furthermore, the term ozone layer depletion makes reference to the thinning of the stratospheric ozone layer, caused by ODS, which allows a greater transmission of Ultraviolet B (UVB) radiation towards the earth's surface, particularly at the poles and nearby regions during certain times of the year [64, 96]. Incoming ultraviolet radiation from the sun, at short wavelengths of about 290-320 nm (UVB radiation), has negative effects on human health (e.g. it can induce skin cancer). However, not just humans are affected by excessive doses of UVB radiation, also the Earth's flora and fauna are harmed by UVB radiation. Among other impacts, overexposure to UVB radiation can lead to eye cataracts and blindness, both in humans and animals, and reduces the quantity and quality of many crop plant species [96].

3.4.1.3 Photochemical Ozone Creation Potential (POCP)

Expressed in terms of the Photochemical Ozone Creation Potential (POCP) of ethylene (C_2H_4), this indicator represents the potential of ozone precursors (e.g. nitrogen oxides (NO_x), volatile organic compounds ($VOCs$), methane (CH_4) and carbon monoxides (CO)) to generate ground level ozone and, therefore, photochemical smog (See Equation C.3 in Appendix C.3) [64]. The photochemical smog (aka summer smog) is a type of smog that is produced when ultraviolet radiation from the sun reacts with ozone precursors in the atmosphere. Mostly during the morning and afternoon, this smog is visible as a brown haze in densely populated areas and warm cities. Moreover, some possible consequences of photochemical smog include: acid rain, reduced visibility and adverse health effects like eye irritation and respiratory diseases, both for humans and animals [97].

Although, the largest contributors of photochemical smog are automobiles, power plants contribute as well to this phenomenon. On one hand, due to the direct emission of ozone precursors by vehicles, photochemical smog cumulates over cities, affecting its inhabitants [97]. On the other hand, power station contribute to this phenomenon mainly via NO_x. In fact, large scale nuclear power emits around 5-8 mg C_2H_4 equiv/kWh, mostly during the mining and milling stage [64].

3.4.2 Water

3.4.2.1 Freshwater and Marine Eco-Toxicity Potentials (FWETP & METP)

Using 1,4-Dichlorobenzene (DCB) as the reference substance, these two indicators assess the potential of chemical stressors to affect freshwater and marine ecosystems, based on the maximum tolerable concentrations of toxic substances by different organisms in these two ecosystems (See Equations C.4 and C.5 in Appendices C.4 and C.5 respectively). Furthermore, the freshwater and marine eco-toxicity potentials account for diverse impacts on water quality, including the presence of toxic compounds, increase of water temperature and other negative effects [64]. In comparison, the energy sector is responsible for 10% of global water withdrawals and electricity generation chains account for more than 50% of all water usage in industrialised and developing countries, given that steam-driven turbines generate most of the world's electricity [64, 98, 99]. Moreover, as an example, the overall freshwater and marine eco-toxicity potentials of large scale nuclear power are 2-4 g DCB equiv/kWh and 6-15 kg DCB equiv/ kWh respectively. The previous, mostly due to the mining, milling and waste disposal stages of the nuclear energy technology electricity generation chain [64].

3.4.2.2 Acidification Potential (AP)

Expressed in terms of the Acidification Potential (AP) of sulphur dioxide (SO_2), this indicator quantifies the contribution of acid gases (e.g. nitrogen oxides (NO_x), hydrogen chloride (HCL) and ammonia (NH_3)) to acid rain and related impacts (See Equation C.6 in Appendix C.6). Acid deposition (aka acid rain) is any type of precipitation (e.g. rain, snow, sleet, hail, or fog) that has a lower pH than normal. Acid rain is generated when water in the air combines with acid gases and then falls down to the Earth's surface. Nonetheless, pollutants may also cumulate on the Earth's surface and rain may combine with them upon its arrival to the ground [100]. Thus, following the emission of acid gases, acid rain causes increased mortality of aquatic organisms and erosion of buildings [64]. Furthermore, acid rain is related to the combustion of fossil fuels and, therefore, power plants which burn fossil fuels and the exhaust from automobiles are some of the sources of acid gases emissions [101]. In relation, although nuclear power does not burn fossil fuels once in operation, the overall acidification potential of large scale nuclear is approximately 40-90 $mgSO_2$ equiv/kWh, mostly due to the mining and milling stages of its electricity generation chain [64].

3.4.2.3 Eutrophication Potential (EP)

Expressed relative to the Eutrophication Potential (EP) of phosphate ions (PO_4^{3-}), this indicator quantifies the potential of nutrients such as nitrogen, phosphorous and ammonia to over-fertilise water and soil (See Equation C.7 in Appendix C.7) [64, 102]. Over-fertilisation of water and soil can result in increased growth of biomass (e.g. algae) in aquatic environments [64]. Similarly, an excessive growth of algae depletes local oxygen, within the corresponding water bodies, and diminishes the biodiversity of aquatic ecosystems. In relation, fertiliser runoffs from farms are the main cause of eutrophication, although other human activities also contribute to this phenomenon [102]. For example, the electricity generation chain of large scale nuclear energy technologies emits around 6-9 mg PO_4^{3-} equiv/kWh [64].

3.4.3 Land

3.4.3.1 Land Occupation and Greenfield Land Use

As a whole, the usage of land has an impact on ecosystems due to the effects of occupation and transformation of land from a near-natural state to one of the following status [64, 66, 103]:

- Transformation to a dump.
- Transformation to industrial area.
- Transformation to traffic area.
- Transformation to reservoir (for hydropower).

Normally, occupation leads to a transformation, but sometimes occupation takes place in an area that was transformed previously [103]. Therefore, at least two indicators are commonly used to assess land use and quality. On one hand, the **land occupation** indicator measures the total land occupied, by a given object of study, and the time period for which the corresponding land is unavailable for other uses or incapable of enhancing biodiversity by succession or cultivation (See Equation C.8 in Appendix C.8) [64]. For example, large scale nuclear power plants occupy land for many years (e.g. 40-60 years during the operational stage and several more during decommissioning), but the amount of land they occupy per unit electricity generated is very small compared to other energy supply technologies [64, 66]. Considering a life cycle approach, large scale nuclear energy technologies occupy approximately $6{\times}10^{-4}\ m^2\ yr/kWh$ [64], while utility scale solar PV[7] and onshore wind farms[8] occupy around $6{\times}10^{-3}\ m^2\ yr/kWh$ and $6{\times}10^{-2}\ m^2\ yr/kWh$ respectively [104].

On the other hand, the **greenfield land use** indicator quantifies the amount of land transformed from a near-natural state, to one of the status previously listed, relative to the total amount of land occupied (See Equation C.9 in Appendix C.9). In addition, this indicator is a rough indicative figure of the impact on biodiversity, caused by the transformation of land. Nevertheless, this indicator depends on the sites proposed for new build. Consequently, there are no typical values of greenfield land use for energy supply technologies, as no generalisation can be done [64].

3.4.3.2 Terrestrial Eco-Toxicity Potential (TETP)

In line with the CML methodology, using 1,4-DCB as the reference substance, this indicator quantifies toxic emissions to land and the potential impact that these may have on different organisms in terrestrial environments (See Equation C.10 in Appendix C.10). For example, the overall terrestrial eco-toxicity potential of large scale nuclear

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[7] Estimated by the author for a PV power plant with 20% efficient modules, based on a land occupation of 9900 $m^2\ yr/GWh$ calculated by [104] for a PV power plant with 13% efficient modules.

[8] Considering wind turbines with a 36% capacity factor.

power is of around 0.4 g DCB equiv/kWh [64]. Furthermore, pollutants access to the terrestrial environments through direct application, diffuse sources or by long-range transport. In consequence, terrestrial organisms (e.g. soil microbes, invertebrates, plants, amphibians, reptiles, birds, and mammals) can be exposed to pollution through dermal, oral, inhalation or food-chain exposure [105].

3.4.3.3 Non-radioactive waste

This indicator measures the aggregated mass of many single species disposed within or as: hazardous waste, incineration, inert material landfill, land farming, municipal incineration, lignite ash, residual material landfill, sanitary landfill or underground deposits [66]. The increasing size and complexity of waste, attributed to the modern economy, represents a serious risk to ecosystems and human health (e.g. air pollution, water and soil contamination) [106]. In relation, it is important to highlight the fact that the non-radioactive waste indicator is a measure of the size of the waste to be disposed and not an estimation of the risk associated with this waste; its calculation method does not include weighting factors to account for the potential harm of each waste type (See Equation C.11 in Appendix C.11). Moreover, regarding energy supply technologies, the electricity generation chains of hard coal and lignite produce the highest amounts of non-radioactive waste, an average of 0.18 kg/kWh. In contrast, combined cycle gas plants and large scale nuclear power plants produce the lowest amounts of solid non-radioactive waste, with averages of 0.003 kg/kWh and 0.006 kg/kWh respectively [67].

3.4.3.4 Radioactive waste

Calculated on a life cycle basis, expressed in units of volume, this indicator addresses the issue of radioactive waste management and intergenerational equity, by estimating the aggregated volume of low level, intermediate level and high level radioactive waste that is produced by a given object of study (See Equation C.12 in Appendix C.12) [64]. For example, in order to maintain the efficiency of nuclear reactors, operators of large scale nuclear power plants remove and replace spent uranium every 18-24 months. Later on, this spent uranium has to be either reprocessed or sent to radioactive waste storage or disposal facilities, given that radioactivity - in high doses - is harmful for living matter (e.g. carcinogenic and genetic effects). Similarly, items contaminated during the operation and maintenance of a nuclear power plant (e.g. protective shoe covers, floor sweepings, paper and plastic) and contaminated items following decommissioning (e.g. parts from inside the reactor vessel) also have to be disposed or stored [6]. Therefore, as suggested by [64], the long-term monitoring burden associated to radioactive waste can be represented by the volume of radioactive waste (or radioactive waste storage facilities) that requires monitoring.

Regarding energy supply technologies, only the electricity generation chain of large scale nuclear power produces significant amounts of radioactive waste directly, although coal ash is often radioactive. As a matter of fact, over its life cycle, large scale nuclear power plants produce an average of around 5×10^{-8} m^3/kWh of radioactive waste[9]. In the case of other electricity generation chains, some small radioactive waste is produced indirectly predominantly owing to nuclear electricity inputs to the chain [67]. Lastly, it should be noted that only high level radioactive waste (primarily spent fuel) represents technical challenges due to its radiotoxicity and long half-life [6].

3.4.3.5 Usage of Non-Renewable Non-Energetic Resources

Based on a life cycle approach and using copper (Cu) [66] or antimony (Sb) as the reference substance [64], this indicator is an indirect measure of the pressure exerted by an energy supply system on the environment [67]. Also known as Abiotic Resource Depletion Potential (ADP) for minerals (See [64]), this indicator quantifies the total amount of non-renewable resources, other than fossil fuels or uranium (e.g. iron ore), required for electricity generation chains (See Equation C.13 in Appendix C.13). In relation, Photovoltaic (PV) technology has the electricity generation chain with the highest consumption of non-renewable non-energetic resources, 9.55×10^{-5} $kg\ Cu$ equiv/kWh [10] or 1.31×10^{-7} $kg\ Sb$ equiv/kWh [11] [67]. Moreover, with a consumption of non-renewable non-energetic resources almost two and half times smaller than that of PV technology, onshore and offshore wind energy technologies follow PV technology with an average requirement of 3.86×10^{-5} $kg\ Cu$ equiv/kWh or 5.27×10^{-8} $kg\ Sb$ equiv/kWh [11] [67]. Next, with an even lower consumption of non-renewable non-energetic resources, large scale nuclear power consumes approximately 5.32×10^{-6} $kg\ Cu$ equiv/kWh or 7.27×10^{-9} $kg\ Sb$ equiv/kWh [11] [67]. Finally, hydro power has the electricity generation chain with the lowest consumption of non-renewable non-energetic resources with a negligible consumption [67].

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[9] Including Low Level Waste (LLW), Intermediate Level Waste (ILW) and High Level Waste (HLW).

[10] Since 2007, the publication year of reference [67], the PV industry has grown dramatically with 80-90% reductions in module costs. Therefore, the original 1.91×10^{-4} $kg\ Cu$ equiv/kWh figure presented by [67] was halved in the present study to account for more efficient PV manufacturing processes which are now available.

[11] The conversion from kg Cu to kg Sb was made using the characterisation factors included in the CML-IA database [89].

3.5 Social Indicators

Although different concepts and models can be used for social indicator research, "in the social sciences no generally agreed-upon model of social indicators exists" [61]. In other words, until today, there is no fundamental theory that can be used to derive social indicators with universal validity [61]. Therefore, in contrast with techno-economic and environmental indicators for energy supply technologies, social indicators are less well established. Social sustainability indicators are mainly qualitative and subjective, given that there is a wide variety of complex social issues that can be related to energy supply technologies [64]. Consequently, acknowledging an unavoidable dose of arbitrariness and with the intention to quantify fundamental social sustainability attributes of energy supply technologies, the social sustainability indicators presented in the following Subsections were selected, or suggested, considering the objective dimension of the quality of life concept and the human capital component of social capital.

On one hand, as mentioned in Section 2.4 , social sustainability intends to, at least, ensure an intergenerationally equitable quality of life for future generations. In relation, the concept of quality of life consists of two dimensions: objective (measurable) and subjective well-being [61]. On the other hand, social sustainability does not claim to maximise individual and overall social welfare, as it focuses on the preservation, more than on the creation, of essential social capital for future generations [59]. In relation, the social capital of a society includes its institutions or formal laws, human capital and cultural capital [21, 60]. Furthermore, while the link of social institutions and cultural capital with energy supply technologies is ambiguous, human capital can be more directly related to energy supply technologies. Human capital relates to human health, education/knowledge, skills/employment, freedom, diversity, security, mobility and access to essential resources/services for a decent standard of living [21, 59]. Finally, although most of the elements of human capital and objective quality of life are addressed by the indicators presented next, some elements (e.g. education/knowledge, freedom, diversity and mobility) were found to be hard to quantify or not clearly linked to sustainable energy technologies.

3.5.1 Access to Essential Services

3.5.1.1 Flexibility

Inspired by the flexibility index suggested by [64] and scored on a 0 - 40 scale, the flexibility indicator, here proposed, reflects the capacity of energy supply technologies to fulfil different possible future energy requirements. As implied by the United Nations Commission on Sustainable Development, sustainable development demands the provision of universal access to a cost-effective mix of energy resources compatible with different needs and locations [7]. This is, "given the uncertainty about the future, ideally, energy supply technologies should be sufficiently flexible to be able to evolve and adapt to the requirements of as wide a range of plausible futures and markets as possible" [68]. As a result, redefining the flexibility index of [64], I suggest the following criteria for the flexibility evaluation of an energy supply technology: ***suitability for off-grid power or small grids (e.g. remote locations), ability to increase production capacity, suitability for trigeneration and ability to produce hydrogen via thermal/thermochemical processes for its use in a hydrogen economy***; with an equal scoring of 10 points each if the corresponding criterion is fulfilled and no points if the corresponding criterion is not fulfilled (See Equation D.1 in Appendix D.1).

- ***Suitability for Off-grid Power or Small Grids:*** although it will be of limited significance in a UK context, this flexibility criterion attends the necessity to expand energy supply beyond urban areas (e.g. isolated areas) and to support electricity services based on grid extensions and/or decentralised energy technologies [7, 25]. Universal access to energy is fundamental not only for economic and social development, but also for the eradication of poverty [7]. However, while it is easy to ask for energy supply technologies suitable for remote locations, there can be inherent limitations. Due to economies of scale, larger sized power plants are being designed and developed. In relation, large power supply units are not suitable for small grids and operating them at less than full power is not profitable [68].

In the early days of electricity generation, power grids were Direct Current (DC) based, and therefore, the distance between generator and consumer was limited, given the low voltage supply. As a result, distributed generation was the rule, rather than the exception. Later, due to technological evolution (e.g. Alternating Current (AC) grids), and economies of scale, it became possible to transmit electricity over longer distances and power generation units became centralised. Nevertheless, the interest in distributed generation has re-emerged, as a result of further technological innovations and a changing economic and regulatory environment (e.g. concerns about climate change) [107]. Lastly, some modern distributed generation technologies include: diesel or gas engines, small gas turbines, the emerging small modular nuclear technology, fuel cells, photovoltaic systems, wind turbines[12] and other renewables (e.g. solar thermal, small hydro, geothermal, etc.) [17, 107, 108].

- ***Ability to Increase Production Capacity:*** in contrast with large sized power plants, many decentralised energy supply technologies can be very flexible in their operation, size and expandability. "The ease of installation of distributed generation allows capacity to be expanded" [108]. For example, the modular design and small size of SMRs makes it possible to have several units on the same site [16]. Unfortunately, not all distributed generation technologies can respond to load changes effectively and the expandability of some energy supply technologies might be compromised by the necessary land occupation. In other words, assuming no land occupation limitations, distributed generation technologies allow capacity expansion, but the capacity of certain generation technologies (e.g. wind power or PV systems) is not always dispatchable due to natural variability [108]. Nevertheless, peak load response and land occupation are sustainable energy indicators measured separately (See Subsections 3.3.2.3 and 3.4.3.1).

- ***Suitability for Trigeneration:*** the potential to provide heating and cooling as well as electricity (aka trigeneration) may be useful in different plausible futures and markets. Usually, a trigeneration plant consists of a gas engine producing electricity and heat (aka cogeneration or combined heat and power), linked to an absorption chiller [109]. In general, recoverable heat generated by CHP plants comes from cooling circuits, engine/generator radiated heat and engine exhaust gases. Heat from cooling circuits is recoverable in the form of hot water, while exhaust gases at a temperature of 400 - $500°C$ can be used in a more direct form in a waste heat boiler to generate steam and for other purposes [110]. As a result, in a trigeneration plant some of the previously mentioned recoverable heat is sent to an absorption chiller which produces chilled water for air conditioning or refrigeration [111].

Thermal power plants, particularly fossil fuelled and nuclear power plants, form the

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[12] "Investments in wind power today are increasingly made in large wind farms by generating companies rather than by individual consumers. In this sense, wind power is more like central generation" [108].

basis of most cogeneration systems and, therefore, they are suitable for trigeneration [112, 113]. For example, the outlet coolant temperature of thermal Light Water Reactor(s) (LWR) and Heavy Water Reactor(s) (HWR) is of around 280 - 325°C and 310 - 319°C respectively, and this theoretically recoverable heat is wasted [64, 113]. Equivalently, according to [113], SMRs are also expected to have outlet coolant temperatures of approximately 280 - 325°C, just as large scale LWRs. In consequence, nuclear reactors could provide trigeneration, if social issues (e.g. proximity to reactors and use of nuclear heat) were overcome [64]. Similarly, although they are not so common, Concentrated Solar Power (CSP) could provide trigeneration as well, since they provide a hot stream at around 400 - 600°C [113, 114]. However, it must be noted that, depending on the temperatures reached by the corresponding systems and coolants, the recoverable and usable heat will be of different quality or grade.

• ***Hydrogen Production via Thermal/Thermochemical Processes:*** by the early 1970s, they idea of hydrogen utilisation for power generation arose in the context of an energy crisis caused by petroleum shortages. On one hand, coupled with effective fuel cell systems, hydrogen may be treated as an energy storage option. Hydrogen is storable in large volumes of compressed gas, absorbed in heavy masses of metal hydride, storable as a cryogenic liquid or through reversible chemical conversion of ammonia, methanol or other chemical forms. As a consequence, today, hydrogen is considered fundamental for the satisfaction of the world future energy demand as hydrogen provides a conversion method for intermittent renewable energies into storable forms [115]. On the other hand, once energy is stored as hydrogen, hydrogen is usable as a fuel in almost all the applications where fossil fuels are used today [113]. Furthermore, in contrast with fossil fuels, steam is the only exhaust from hydrogen combustion and this exhaust is absorbed by nature with no or very limited environmental impact. Unfortunately, hydrogen is rarely available in its free form on earth and, therefore, hydrogen has to be produced via an energy intensive process (e.g. water electrolysis, thermochemical water splitting, gasification, hydrogen reforming, photocatalysis and photo-biochemical conversion) where hydrogen is extracted from other materials (e.g. water, biomass, hydrogen sulphide and hydrogen-rich petroleum resources) [115].

Among the previously mentioned hydrogen-rich substances, water is the most abundant source of hydrogen [113]. In relation, while there are four basic energy conversion pathways for hydrogen production (e.g. thermal, electrical, biochemical and photonic), large scale hydrogen production from water is mainly attainable through the usage of thermal and electrical energy sources for thermochemical processes and electrolysis respectively [115]. Furthermore, while the electricity required for electrolysis can be generated by any energy supply technology, the heat required for thermochemical water splitting is not released by all energy supply technologies. Hydrogen production via thermochemical processes requires temperatures of around 500 - 900$^{\circ}C$ [113]. Thus, in this context, although the outlet coolant temperature of typical thermal LWRs and of developing SMRs is approximately 280 - 325$^{\circ}C$, much higher temperatures are required for hydrogen production [64]. In contrast with gas fired power plants and CSP (See the *Ability for Trigeneration* flexibility criterion above), in general, nuclear energy technologies would not be capable of providing enough heat for large scale hydrogen production, except for the developing High Temperature Gas Reactor(s) (HTGR) and the future Gas Cooled Fast Reactor(s) (GFR), Molten Salt Reactor(s) (MSR) and Lead-cooled Fast Reactor(s) (LFR) [113, 115].

3.5.2 Skills/Employment

3.5.2.1 Total Employment

This indicator quantifies the overall (direct and indirect) employment created over the life cycle of a given object of study (e.g. a power plant), considering the time during which this employment is supported (See Equation D.2 in Appendix D.2). In contrast with indicators that represent the absolute number of jobs created per total electricity generated, the total employment indicator attends the fact that the employment provided by a power plant changes significantly throughout its life cycle stages [64]. Furthermore, in this context, direct employment refers to the jobs associated with the production and delivery of energy products (e.g. construction, operation, maintenance and decommissioning life cycle stages of power plants). Likewise, indirect employment highlights the employment created and sustained in sectors supplying a given energy project with goods and services (e.g. fuel mining, fuel production, waste management and others) [64, 6]. In relation, indirect employment must not be confused with induced employment, as induced effects are caused by the spending associated with direct and indirect employment (e.g. by the spending of salaries) [6].

Without considering the jobs supported due to the manufacture of components, the construction stage of large scale nuclear power plants provide more than 1000 jobs for approximately 6 years. Similarly, following the construction stage, during an average operating life of 60 years, large scale nuclear power plants sustain around 500 jobs on-site [64]. On a life cycle basis, large scale nuclear power is one of the energy supply technologies that employ the fewest people, as it provides 81 $person-yr/TWh$ of total employment. In contrast, offshore wind and PV provide the highest total employment, with 368 and 653 $person-yr/TWh$ respectively (See Figure 3.1). In part, renewables achieve high total employment figures due to their relatively low capacity factors, which lead to comparably low electrical outputs [116].

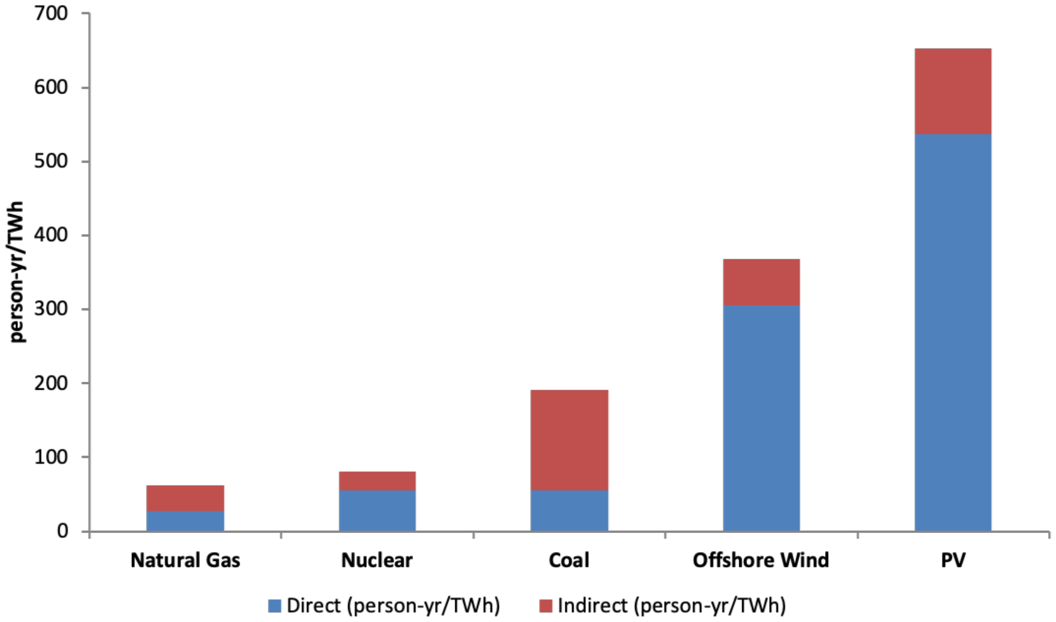

Figure 3.1: Total Employment indicator of Several Energy Supply Technologies. Source: [116]

Lastly, the results presented in Figure 3.1 may look significantly different if the total employment was presented per average capacity instead of per total electricity generated, as shown by [6, 117]. In other words, employment results and statistics of energy technologies may vary depending on the chosen reporting method.

3.5.3 Local Community Impact

3.5.3.1 Proportion of Staff Hired from Local Community

Expressed relative to total direct employment, the proportion of staff hired from the corresponding local community is an indirect measure of the contribution of a given object of study to the social development and welfare of local communities. Although this indicator should be based on a life cycle approach, [64] recommends the consideration of only the operational life cycle stage of energy supply technologies (See Equation D.3 in Appendix D.3). The previous attends to the fact that employment information regarding whole electricity generation chains might not be available at a given time, or not available at all, as different companies might be involved. Consequently, [64] suggests that the proportion of staff hired from local communities might be measured only by individual companies with specific knowledge regarding their impact on the local community. Nonetheless, this indicator was included in this framework in order to illustrate the inherent difficulty of measuring progress towards social sustainability goals, particularly at the local level.

3.5.4 Human Health

3.5.4.1 Human Toxicity Potential (HTP)

Similar to the freshwater, marine and terrestrial eco-toxicity potentials, using 1,4-DCB as the reference substance, the Human Toxicity Potential (HTP) indicator expresses the potential harm to human health caused by toxic emissions to air, water and soil; excluding health impacts from radiation which is quantified separately by another indicator (See Equation D.4 in Appendix D.4) [64]. Moreover, the HTP of 1,4-DCB emitted to air is defined as unity and the medium-dependent HTP factors of toxic substances are expressed relative to the HTP of 1,4-DCB emitted to air. Additionally, resembling the GWP factors (see Subsection 3.4.1.1), the HTP factors of toxic substances vary depending on the time horizon used for the impact assessment (20, 100, 500 years and infinite) [88]. In relation, according to the CML method [88], HTP factors derived by considering an infinite time horizon and global spatial scale are generally adopted and, therefore, here recommended.

Regarding energy supply technologies, on a life cycle basis, large scale nuclear emits substantial amounts of heavy metals (e.g. arsenic and chromium), mostly from uranium mill tailings. In contrast with the 5.4 g 1,4-DCB/kWh of gas fuelled power plants, large scale nuclear power, with a HTP of 115 g 1,4-DCB/kWh, is tentatively the most toxic energy supply technology for humans [116]. Nevertheless, according to [6], due to the difficulties of finding accurate HTP factors, the overall HTP of energy supply technologies remains variable among different life cycle impact assessment methods. In other words, "there is currently a disagreement between LCA impact methodologies over HTP results" [116]. Thus, further research in this area is warranted.

3.5.4.2 Human Health Impacts from Radiation (HIR)

Expressed in terms of Disability Adjusted Life Years (DALY), this indicator measures the human health-related consequences of the release of radioactive substances and/or direct exposure to radiation, but without considering health effects due to occupational exposure (See Equation D.5 in Appendix D.5) [88, 118]. The DALY unit captures the time lost through premature death (e.g. cancer), and the time lived with a disability of specified severity and duration (e.g. a hereditary disease)."One DALY is one lost year of healthy life" [119].

As a result of a radioactive decay process, different forms of radiation may be released (e.g. alpha, beta, gamma and neutron radiation). Also known as ionising radiation, these forms of radiation add or remove electrons to or from the atoms they encounter. However, the degree of ionisation is different depending on the type of radiation, exposure and material irradiated [88]. In relation, "the nuclear fuel cycle, phosphate rock extraction, coal power plants, and even oil and gas extraction are man-made sources of air and waterborne radionuclide releases to the environment" [118]. Nevertheless, for obvious reasons, the radiation related human health impact of large scale nuclear power is an order of magnitude greater than that of any other electricity generation chain. On a life cycle basis, large scale nuclear power results in approximately 0.02 DALY/GWh, of which 90% is attributed to Radon-22 emissions to air from uranium mine tailings and the remaining 10% is a result of the emission of isotopes during the operation life cycle stage [64, 116].

3.5.5 Human Security

3.5.5.1 Risk of Severe Accident and Maximum Credible Number of Fatalities per Accident

Based on historical records and probabilistic safety assessments, these two indicators estimate the probability of occurrence of large accidents, due to complete electricity generation chains, and the maximum credible number of fatalities per accident. While the risk of severe accident indicator (aka large accident risk [64], severe accident [66] or fatality rate [120]) is expressed in fatalities per unit electricity generated, the maximum consequences per severe accident are represented as the maximum credible number of fatalities per accident. Moreover, the Paul Scherrer Institute (PSI), uses its Energy-related Severe Accident Database (ENSAD) for accident-related estimations regarding fossil fuels and hydro power. In the case of nuclear energy technology, the PSI applies a Probabilistic Safety Assessment (PSA). Lastly, for renewables, the risk of severe accidents and maximum consequences per severe accident are estimated by the PSI "based on a combination of available data, modelling and expert judgement" [120]. Therefore, an accurate calculation of these two indicators is not possible without access to the corresponding explicit calculation methods and to vast historical databases of the energy sector.

As a result of the public suspicion and fear engendered by the three major nuclear accidents (See Subsection 1.1.1), particularly Chernobyl[13], large accidents in electricity generation chains are mostly associated with nuclear power, by the public perception. However, it is important to highlight the fact that Chernobyl is the only data point, regarding large accident fatalities from nuclear plants. In other words, large accidents occur more often in other electricity generation chains, but with fewer consequences per accident [64]. On one hand, using PSAs and OECD historical data, the PSI has estimated that large scale nuclear power holds a risk of severe accident of 0.007 fatalities/$GWyr$, while the electricity generation chain of coal holds a risk of severe accident of 0.12 fatalities/$GWyr$ (See Figure 3.2) [120]. On the other hand, the maximum number of credible fatalities due to a nuclear accident has been estimated to be 24 times higher than that of coal-related accidents, 6596 and 272 fatalities respectively (See Figure 3.3) [64, 120]. Lastly, new generation III PWR reactors (e.g. European Pressurized Reactor(s) (EPR)) are expected to hold a significantly lower risk of severe accident

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[13] The Chernobyl nuclear accident resulted in approximately 8,250 - 200,000 fatalities, including latent deaths [64].

than currently operating nuclear power plants due to safety augmenting systems, but higher maximum consequences per severe accident due to larger radioactive inventories. Whilst it has been estimated that EPRs could result in a severe accident with 7 times more deaths than those linked to PWRs, the fatality rate (fatalities/$GWyr$) of EPRs has been projected to be 700 times lower than that of PWRs [120]. Nevertheless, the data used to estimate these figures and the workings behind this data are not evident from reference [120].

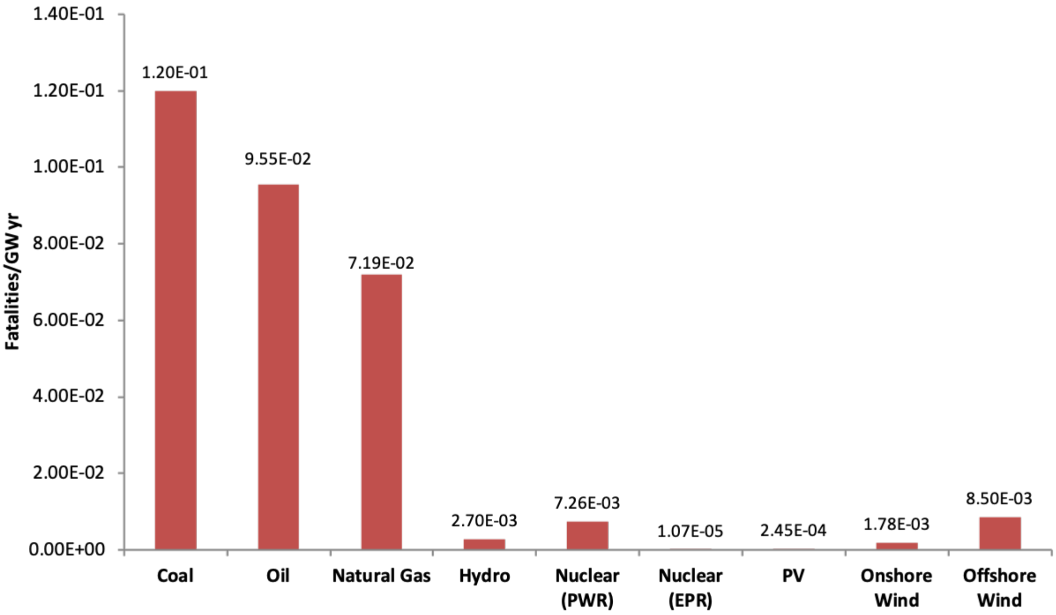

Figure 3.2: Risk of Severe Accident per Energy Supply Technology.
Source: [120]

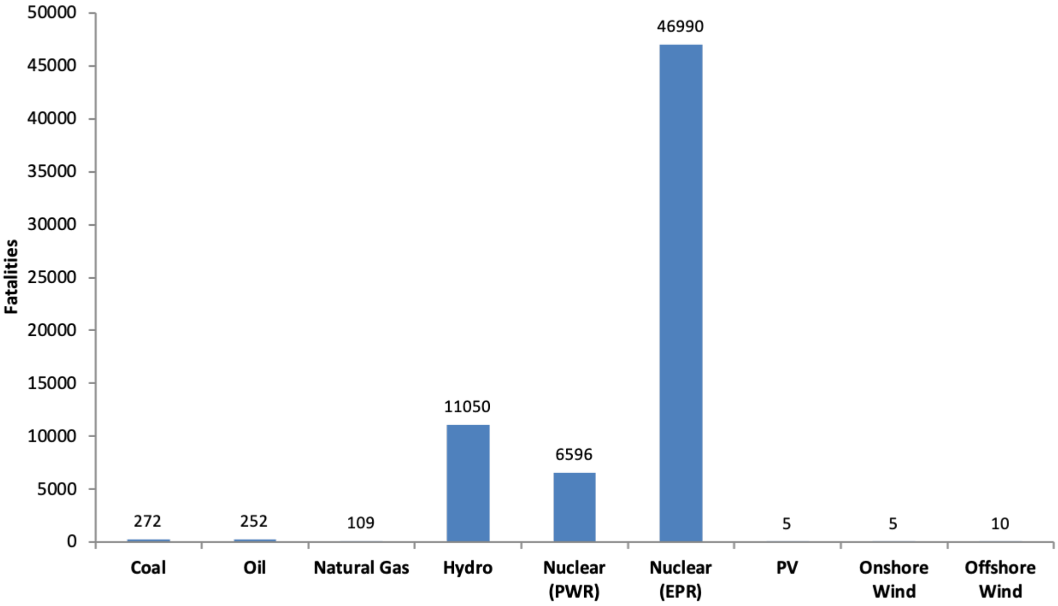

Figure 3.3: Maximum Credible Number of Fatalities per Accident per Electricity Generation Chain.
Source: [120]

3.5.5.2 Nuclear Proliferation

Only applicable to nuclear technologies, expressed as a score on a 0 - 3 scale, this indicator represents the extent to which a given nuclear technology enhances the danger of a nuclear war (See Equation D.6 in Appendix D.6). This is, the nuclear proliferation indicator reflects the degree to which a given nuclear technology promotes a wider dissemination of nuclear weapons and ultimately prevents nuclear disarmament. Furthermore, weapon-grade plutonium is the usual focus of nuclear proliferation resistance indicators. Consequently, from a proliferation perspective, this indicator considers three equally weighted main criteria, as suggested by [64]:

1. ***Usage of non-enriched uranium in a reactor capable of online refuelling (e.g. CANDU or Magnox reactors)***

   On one hand, reactors that use non-enriched uranium have significantly higher production of weapon-grade plutonium than reactors that use enriched uranium, due to a lower fuel burnup. On the other hand, online refuelling makes easier the extraction of low burnup spent fuel [64].

2. ***Use of reprocessing***

   Following a partitioning process, irradiated fuel can be separated into uranium (U), plutonium (Pu), minor actinides, some long-lived fission products and waste. Later, as a result of a transmutation process, uranium (U), plutonium (Pu), neptunium (Np) and americium (Am) can be re-fabricated into nuclear fuel [121]. Unfortunately, reprocessing leads to risks such as plutonium theft or detonation [64]. Therefore, the usage of reprocessed fuel depends more on site dependent socio-political regulations than on nuclear reactor designs.

3. ***Requirement for Enriched Uranium***

   The requirement for enriched uranium may contribute to the spread of enrichment technology worldwide [116]. If enrichment technology is required for civil nuclear power, "it is diplomatically and politically difficult for a possessor of that technology to deny it to a country that does not possess it" [64]. This is, in general, possessing nuclear power encourages other countries to pursue nuclear technology [64].

3.5.6 Energy Security

3.5.6.1 Fuel Energy Density

Expressed in terms of energy content per unit mass or unit volume, the fuel energy density indicates implicitly the ease of storage of different types of fuels and, therefore, it is related to energy security (See Equation D.7 in Appendix D.7). Similarly, fuel extraction activities, transport requirements, environmental releases and waste, are all determined by the corresponding fuel energy density. For example, with approximately 21 GJ/m^3 and 0.035 GJ/m^3 respectively, coal and gas have relatively low energy densities. Consequently, given that their stockpiling is difficult, disruptions in the gas and/or coal supply chains can leave entire countries vulnerable to electricity supply shortages. In contrast, assuming a 50 GWd/tU - Gigawatt-day per tonne of Uranium - burnup, a light water PWR fuel assembly has an energy density of approximately 10 million GJ/m^3 which allows stockpiling between 476,000 to 286 million times more energy in the same volume compared to coal and gas respectively. As a result, the high energy density of nuclear fuel is an advantageous characteristic, in comparison to other fuels for electricity generation (See Table 3.6) [64].

Table 3.6: Energy Density of Typical Fuels.
Source: [6]

Fuel (1 kg)	**Coal Equivalent (kg)**	**Available Energy (kWh)**
Coal	1	8.2
Gas	1.1	9
Oil	1.4	12
Uranium	2.7 million	50,000

3.5.7 Intergenerational Equity

3.5.7.1 Critical Waste Confinement Time

Expressed in multiples of 1000 years, this indicator aims to illustrate the potential intergenerational harm from hazardous waste. For example, as indicated in Subsection 3.4.3.4, operators of large scale nuclear power remove and replace spent fuel (nuclear waste) every 18 - 24 months. Moreover, radioactive waste reaches the radiotoxicity level of natural uranium ore in several hundred thousand years in the case of open fuel cycle systems, and several centuries in the case of closed fuel cycle systems (See Table 3.7). Unfortunately, while nuclear waste is the most documented waste stream, consistent data regarding waste streams from other electricity generation chains is scarce. “In most countries, waste from coal power generation is not yet classified as hazardous despite its heavy metal content” (e.g. lead, mercury, arsenic, cadmium, nickel and acid gases) [6]. Similarly, depending on the manufacturing process and the corresponding energy conversion efficiency, the manufacture of PV cells also generates hazardous waste. At the end of its lifetime, if not disposed properly, PV panels might be a threat to humans and the environment due to lead and cadmium leaching [6].

Table 3.7: Critical Waste Confinement Time of Different Electricity Generation Chains.
Source: [6, 66]

Electricity Generation Chain	**Critical Waste Necessary Confinement Time (order of magnitude, multiple of 1000 years)**
Lignite	50
Hard Coal	50
Oil	0.1
Natural Gas	0.01
Nuclear (Open Fuel Cycle)	100
Nuclear (Closed Fuel Cycle)	0.1
Hydro	0.01
Wind	1
PV	50

On one hand, although long confinement times for long-life high level radioactive waste raises public concern, new reprocessing methods (e.g. partitioning and transmutation) may reduce the confinement time required for nuclear waste. Alternatively, fast reactors reduce the amount of transuranic elements (Pu and Am) for final disposal by a factor of about 200, given that all actinides can be recycled. On the other hand, it is generally agreed by the nuclear community that safe isolation of disposed high level radioactive waste is assured in stable geological formations combined with engineered barriers. “Continental shield rocks have proven their geological stability, as well as their favourable geochemical conditions and limited water movement, over hundreds of millions years” [6]. Geological disposal limits radiation leakages/released doses to a maximum of 0.1% of the background natural radioactivity [6].

3.6 Chapter Summary

Sustainable Energy Supply Indicators

- Having identified the main goals and impact areas addressed by sustainable development in Chapter 2, in order to assess the economic sustainability of SMRs in further Chapters, in this Chapter a set of 40 sustainable energy supply indicators was put together. In relation, although this study focuses only on economic sustainability, non-economic sustainability indicators were included in this set with the intention to provide decision and policy makers with the necessary tools to assess other aspects of sustainability.
- **Unique Contribution:** Different to previous sets of sustainable energy supply indicators, 30 indicators were allocated to the so-called 'three pillars of sustainability' - economic, social and environmental - and an extra set of 10 indicators was allocated to a new 'pillar of sustainability': Attractiveness of Investment.
  - While consumer economic welfare is addressed by the techno-economic sustainability indicators, sustainable energy supply systems cannot be developed and deployed if they are not sufficiently attractive/profitable to justify doing so. Therefore, the attractiveness of investment indicators are necessary to measure the extent to which an energy supply technology fulfils market actor interests and, in consequence, the likelihood of a given energy supply technology to be released to the market and compete with other already available technologies.

Chapter 4

ECONOMIC CHARACTERISATION OF SMALL MODULAR NUCLEAR REACTORS IN A UK SCENARIO

4.1 SMR of Interest

According to the IAEA [122], Small Modular Reactors (SMRs) are defined as advanced reactors of up to 300 MWe, designed to be built in a factory environment and shipped to utilities for installation. Furthermore, the most mature SMR concepts are evolutionary variants of Light Water Reactors (LWRs) currently operating worldwide [123]. Therefore, in a UK context, the term SMRs is reserved for Generation III/III+ LWRs with output power capacities of up to 300 MWe, although the term is applied to some larger reactor designs. In the UK, small modular non-LWRs which use novel cooling systems or fuels are known as Advanced Modular Reactors (AMRs) [124].

As a result of a UK Government request, in 2014, the National Nuclear Laboratory (NNL) produced a feasibility study (See [17]) where the view of the UK Industry regarding SMRs was captured. Furthermore, in order to produce this study, the NNL undertook a review to determine the viability of SMRs, the potential UK industry role and the possible role of UK Government. As a result, the NNL identified the

SMR technologies shown in Table 4.1 as those that are closest to commercial operation (deployable in-service dates within a 10 year timeframe).

Table 4.1: SMR technologies that are closest to commercial operation.
Source: [17].

SMR	**Vendor / Developer and Country**	**Basic Description**
NuScale SMR	NuScale Power LLC (Fluor) - US	160 $MWth$ / 50 MWe Integral Pressurised Water Reactor modules, deployed as up to 12 modules per site (600 MWe site nominal).
B&W mPower[14] SMR	Generation mPower LLC (Joint venture between Babcock & Wilcox Company and Bechtel Power Corporation) - US	530 $MWth$ / 180 MWe Integral Pressurised Water Reactor, deployed as up to 2 reactors per building (360 MWe).
Westinghouse SMR	Westinghouse Electric Company - US	800 $MWth$ / 225 MWe Integral Pressurised Water Reactor.
ACP100 SMR	China National Nuclear Corporation (CNNC) - China	310 $MWth$ / 100 MWe Pressurised Water Reactor.
AREVA[15] SMR	AREVA - France	∼150 MWe Integral Pressurised Water Reactor.
SMART[16] SMR	SMART Power Co. Ltd. - Korea	330 $MWth$ / 100 MWe Integral Pressurised Water Reactor [125].

From Table 4.1, it is clear that Integral PWRs are the SMRs that are closest to commercial operation in the UK, although many SMR designs are being developed around the world. Therefore, in order to illustrate potential SMR worldwide future trends, Table 4.2 shows a basic description of: (1) Three Pressurised Water Small Modular Reactor conceptual designs acknowledged by the IAEA in its Advanced Reactors Information System (ARIS) (See [126]), (2) The recently presented Rolls-Royce SMR [127] and (3) An SMR conceptual design proposed by an international consortium led by Westinghouse Electric Company [128].

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[14] Although, in 2014, B&W scaled back spending on the mPower SMR due to funding constraints, the maturity of the design suggests that this is a viable opportunity for the UK [17].

[15] "Since the AREVA review further contact has indicated that AREVA will not be looking to develop SMR technology in the near future" [17].

[16] Little design and development is required to bring this reactor to market and, therefore, there is a lack of opportunity for the UK to participate in the development programme [17]. This SMR has already been licensed by the Nuclear Safety and Security Commission (NSSC) in Korea [125].

Table 4.2: Pressurised Water SMR conceptual design trends.
Source: [126, 127, 128].

SMR	**Vendor / Developer and Country**	**Basic Description**
UK SMR	Rolls-Royce PLC - UK	1200-1350 $MWth$ / 400-450 MWe Integral Pressurised Water Reactor.
Fixed Bed Nuclear Reactor	Federal University of Rio Grande do Sul - Brazil	218 $MWth$ / 72 MWe Pressurised Water Reactor.
Integrated Modular Water Reactor	Mitsubishi - Japan	1000 $MWth$ / 350 MWe Integral Pressurised Water Reactor.
VBER-300	OKBM - Russia	917 $MWth$ / 325 MWe Pressurised Water Reactor.
IRIS	International Consortium Led by Westinghouse Electric Company	1000 $MWth$ / 335 MWe Integral Pressurised Water Reactor.

On one hand, from Table 4.1 and Table 4.2, most of the SMRs identified as feasible by the NNL, and other SMRs in conceptual design stage, have an output power capacity within the 50 - 300 MWe range. On the other hand, in order to calculate several financial figures of merit, cost escalations can be done assuming economies of scale. Nevertheless, as discussed in further sections (See Subsection 4.2.3), so far the economies of scale assumption has been proven to be true for nuclear power, but only in the 300 - 1300 MWe range. In other words, it is still unknown if nuclear reactors with a power output smaller than 300 MWe follow economies of scale or not. Consequently, a generic Integral Pressurised Water Small Modular Reactor of 300 MWe would have a similar output power capacity to that of the most feasible SMRs and would also be a good candidate for cost estimations assuming economies of scale.

4.2 Overnight Cost

The capital investment required to construct a nuclear power plant represents approximately 60%[17] of the total electricity generation costs of nuclear power, while fuel costs and O&M costs account for 20% each. In other words, out of the three major cost components of nuclear power, the capital cost is the cost element that contributes the most to the total cost. Furthermore, the economic competitiveness of nuclear power has been weakened over the past decade due to technological progress of other electricity supply technologies and to lower fossil fuel prices in the international markets. As a result, nuclear power will only remain economically competitive against fossil fuels and renewable sources if significant cost reductions are achieved through technological progress (e.g. series production and improved reactor designs) [129].

The total capital costs not only of nuclear power plants, but of any power plant are the overall costs leading from initial site investigation to commercial operation. This is, in addition to direct and indirect costs, the capital investment required for a power plant includes supplementary costs, financial costs and owner's cost. However, experts have found that “financial costs are so country, time, and project specific that a generic evaluation of financial costs is meaningless” and, therefore, financial evaluations of power plants normally focus only on the overnight cost [129]. In relation, the overnight cost is the cost of a construction project if no interest was accrued during construction. Alternatively, [68] defines overnight cost as: “the present value cost that would have to be paid as a lump sum up front to completely pay for a construction project”.

In the nuclear sector, the overnight cost is understood as the base construction cost (direct and indirect costs) plus owner's, contingency and first core costs [130]. Moreover, according to [129] the following overnight cost breakdown structure is applicable to all types of nuclear reactors and any type of contractual approach:

- Direct Costs.
    - Land and land rights.
    - Reactor plant equipment.
    - Turbine-generator plant equipment.
    - Electrical and Instrumentation & Control equipment.
    - Water intake, and discharge, and heat rejection.

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[17] 65-85% if the interests accrued during construction are included [79].

Miscellaneous plant equipment.

Construction at the plant site.

- Indirect Costs.

  Design and engineering services.

  Project management services.

  Commissioning.

- Other Costs.

  Training and technology transfer.

  Taxes and insurance.

  Transportation.

  Owner's cost.

  Spare parts.

  Contingencies.

4.2.1 Microeconomics Background: Long-Run Cost Curves and Economies of Scale

First, a firm's total cost is the sum of all economic costs that a firm incurs when it uses labour and capital to produce output [131]. In other words, a firm's cost determines its supply and, at the same time, supply and demand determine price. Therefore, it is necessary to understand the nature of costs in order to comprehend the forces behind supply and the process of price determination [132].

4.2.1.1 Long-Run vs. Short-Run Cost Curves

On one hand, long-run total cost curves show how a firm's minimised total cost varies with output when the firm is free to adjust all its inputs. On the other hand, short-run total cost curves show the minimised total cost of producing Q units of output when at least one input is fixed at a particular level [131].

4.2.1.2 The Long-Run Total Cost Function

The total cost function (TC) expresses a functional relationship between the total cost and factors that determine it. In relation, usually, the factors that determine the total cost function (TC) are: output (Q), level of technology (T), fixed factors (F) and the prices of factors (P) (See Equation 4.1) [132].

$$TC = f(Q, T, F, P) \tag{4.1}$$

However, such a complex total cost function requires multidimensional analysis and, therefore, the following assumptions are usually made to simplify the cost analysis [132]:

- A firm produces a single homogeneous good employing fixed and known quantities of fixed factors of production, whatever the level of output (Q) of the firm in the short run.
- The technology used for the production is known and fixed.
- The firm adjusts the employment of variable factors in such a way that a given output Q of the good is produced at the minimum possible total cost.

Thus, following the previously mentioned assumptions the long-run total cost function, denoted by $TC(Q)$, shows how minimised total cost varies with output, holding input prices fixed and selecting inputs to minimise cost [131]. Similarly, the long-run total cost curve must be increasing with Q, and must equal to zero when $Q = 0$ [133].

4.2.1.3 Long-Run Average and Marginal Costs

On one hand, long-run average cost ($AC(Q)$) is the firm's cost per unit output and it equals the long-run total cost divided by the output (See Equation 4.2). On the other hand, the long-run marginal cost ($MC(Q)$) is the rate at which long-run total cost changes with respect to a change in output and it equals the slope of $TC(Q)$ (See Equation 4.3) [133].

$$AC(Q) = \frac{TC(Q)}{Q} \tag{4.2}$$

$$MC(Q) = \frac{dTC(Q)}{dQ} \tag{4.3}$$

Furthermore, the relationship between average cost and marginal cost is such that [133]:

- $AC(Q) > MC(Q)$ when $AC(Q)$ is decreasing in Q.
- $AC(Q) < MC(Q)$ when $AC(Q)$ is increasing in Q.
- $AC(Q) = MC(Q)$ when $AC(Q)$ is at a minimum.

4.2.1.4 Economies and Diseconomies of Scale

The variation of long-run average cost as output increases is the basis for two important concepts: economies of scale and diseconomies of scale. A firm benefits from economies of scale when the average cost decreases when output increases. Furthermore, economies of scale may result from: (1) physical properties of processing units that lead to increasing returns to scale in input, (2) specialisation of labour or (3) the need to employ indivisible inputs[18]. In contrast, a firm suffers from diseconomies of scale when the average cost increases as output increases. Diseconomies of scale are usually attributed to managerial diseconomies, when an increase in output forces a firm to increase its spending on managerial services by more than the percentage increase in output [131].

4.2.1.5 The Output Elasticity of Total Cost as a Measure of Economies of Scale

Elasticities of demand (e.g. price elasticity of demand or income elasticity of demand) tell us how sensitive demand is to factors that drive demand (e.g. price or income). Similarly, elasticities can be used to show how sensitive the total cost is to the factors that influence it. Consequently, holding input prices fixed and selecting inputs to minimise cost, the output elasticity of total cost ($\epsilon_{TC,Q}$) is the percentage change in total cost per 1 percent change in output and it is equal to the ratio of marginal to average cost (See Equation 4.4) [131].

$$\epsilon_{TC,Q} = \frac{\frac{dTC(Q)}{TC(Q)}}{\frac{dQ}{Q}} = \frac{\frac{dTC(Q)}{dQ}}{\frac{TC(Q)}{Q}} = \frac{MC(Q)}{AC(Q)} \tag{4.4}$$

Consequently, following the relationship between average cost and marginal cost, the output elasticity of total cost tells us the extent of economies of scale as shown in Table 4.3.

Table 4.3: Relationship between Output Elasticity of Total Cost and Economies of Scale.
Source: [131]

$\boldsymbol{\epsilon_{TC,Q}}$	**MC(Q)** vs. **AC(Q)**	**Economies vs. Diseconomies of Scale**
$\epsilon_{TC,Q} < 1$	$MC(Q) < AC(Q)$	Economies of Scale
$\epsilon_{TC,Q} > 1$	$MC(Q) > AC(Q)$	Diseconomies of Scale
$\epsilon_{TC,Q} = 1$	$MC(Q) = AC(Q)$	Neither

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[18] “An indivisible input is an input that is available only in a certain minimum size; its quantity cannot be scaled down as the firm's output goes to zero” [131].

4.2.1.6 The Output Elasticity of Average Cost as a Measure of Economies of Scale

Upon replacing $TC(Q)$ with $TC(Q)/Q$ in Equation 4.4, the output elasticity of average cost can be derived as follows (See Equation 4.5).

$$\epsilon_{AC,Q} = \frac{\frac{d(\frac{TC(Q)}{Q})}{dQ}}{\frac{(\frac{TC(Q)}{Q})}{Q}} = \frac{\frac{\frac{dTC(Q)}{dQ}\times Q - TC(Q)}{Q^2}}{\frac{TC(Q)}{Q^2}} = \frac{dTC(Q)}{dQ} \times \frac{Q}{TC(Q)} - 1 \quad (4.5)$$

Furthermore, recalling Equation 4.4, Equation 4.5 can also be expressed in terms of the output elasticity of total cost (See Equation 4.6).

$$\epsilon_{AC,Q} = \frac{dTC(Q)}{dQ} \times \frac{Q}{TC(Q)} - 1 = \epsilon_{TC,Q} - 1 \quad (4.6)$$

Consequently, not only the output elasticity of total cost, but also the output elasticity of average cost can be used to measure the extent of economies of scale (See Table 4.4).

Table 4.4: Relationship between Output Elasticity of Average Cost and Economies of Scale.
Source: [132]

$\boldsymbol{\epsilon_{AC,Q}}$	**Economies vs. Diseconomies of Scale**
$\epsilon_{AC,Q} < 0$	Economies of Scale
$\epsilon_{AC,Q} > 0$	Diseconomies of Scale
$\epsilon_{AC,Q} = 0$	Neither

4.2.2 Capital Investment Cost Estimation Techniques

As noted by [134], capital cost estimating is essentially an intuitive process that attempts to forecast the final outcome of a future capital expenditure program (or project) for which not all parameters and conditions are known or fully defined. Moreover, estimates vary depending on the availability of information, time constrictions and the purposes of the estimates. As a result, the American Association of Cost Engineers (AACE) has proposed the following classification of cost estimating techniques (See Table 4.5):

Table 4.5: Classification of Capital Cost Estimating Techniques.
Source: American Association of Cost Engineers (AACE).

Technique	**Probable Accuracy**	**Method of Preparation**
Order of Magnitude	-30% to +50%	Cost-capacity curves and cost-capacity ratios are used.
Budget	-35% to +30%	Made for the owner's budget. Flowsheets, layouts, and equipment details are used.
Definitive	-5% to +15%	Defined engineering data such as site data, specifications, basic drawings, and detailed sketches are used.

Nonetheless, typically, cost estimates fall into two major categories: preliminary and detailed. On one hand, preliminary estimates are made when there is a lack of definitive or verifiable information for the initial evaluation of a project. Furthermore, preliminary estimates use personal experience and judgement, historical cost charts, rules of thumb, and simple mathematical calculations to obtain quick and inexpensive cost estimates. In consequence, preliminary cost estimating techniques (e.g. order of magnitude, conceptual, factored, quickie, and feasibility estimates) usually have a very low accuracy [134].

On the other hand, detailed estimates can only be obtained once the scope and schedule of a project have been defined. Moreover, detailed cost estimates are based on quantitative information and rigorous formal procedures. As a result, this cost estimates have an increased accuracy, but require more time, effort, and expense. Finally, detailed estimates are also known as: definitive, semi-definitive, budget, check, final, official or defined estimates [134].

4.2.2.1 Preliminary Power Law or Cost-to-Capacity Estimation Technique

An exponent estimating technique known as Cost-Capacity relationship [134], Cost-to-Capacity Model [135] or Plant-Capacity Ratio [136] is often used to prepare preliminary capital cost estimates. This technique is based on the widely observed and accepted idea that the cost of a piece of equipment, or of entire plants, is proportional to a fixed power of its capacity. Moreover, Equation 4.7 resembles a long-run total cost function (introduced in Subsection 4.2.1.2) and illustrates the main idea behind the Cost-to-Capacity model.

$$CC(Q) = aQ^{n_{Tot}} \tag{4.7}$$

Where:

- $CC(Q)$: Capital cost of a piece of equipment, or a plant, as a function of its capacity or output.
- a: Constant.
- Q: Capacity or output of the corresponding piece of equipment or plant.
- n_{Tot}: Output elasticity of capital cost.

In relation, no previous work was found to refer to the so-called n exponent as the output elasticity of capital cost (n_{Tot}), although it is treated as such. This exponent is normally known just as scale exponent, scaling coefficient, cost-capacity factor or economy-of-scale exponent [134, 135, 137]. As a result, this power law estimation technique is often used in an inappropriate and inconsistent manner.

Furthermore, upon dividing both sides of Equation 4.7 by Q and recalling the definition of average cost (Equation 4.2), the Cost-to-Capacity model can be used to calculate the average capital cost, or capital cost per unit capacity, of a given object of study (See Equation 4.8).

$$ACC(Q) = aQ^{n_{Tot}-1} = aQ^{\beta_{Tot}} \tag{4.8}$$

Where:

- $ACC(Q)$: Average capital cost (or capital cost per unit capacity) of a piece of equipment, or a plant, as a function of its capacity or output.
- a: Constant.
- Q: Capacity or output of the corresponding piece of equipment or plant.
- n_{Tot}: Output elasticity of capital cost.
- β_{Tot}: Output elasticity of average capital cost.

Nevertheless, most of the time it is easier to compare the capital cost, or the average capital cost of two similar objects of study with different capacities. Therefore, the Cost-to-Capacity model (Equations 4.7 and 4.8) is normally found in terms of two objects of study with different capacities, as shown next (See Equations 4.9 and 4.10).

$$\frac{CC_1(Q_1)}{CC_2(Q_2)} = \frac{a_1}{a_2}\left(\frac{Q_1}{Q_2}\right)^{n_{Tot}} \tag{4.9}$$

$$\frac{ACC_1(Q_1)}{ACC_2(Q_2)} = \frac{a_1}{a_2}\left(\frac{Q_1}{Q_2}\right)^{n_{Tot-1}} = \frac{a_1}{a_2}\left(\frac{Q_1}{Q_2}\right)^{\beta_{Tot}} \tag{4.10}$$

Where the subscripts (1,2) stand for two different objects of study and by convention it is assumed that $a_1 = a_2$ [135]. As a result, the Cost-to-Capacity model can be re-written in such a way that it allows cost estimations to be undertaken for a particular facility or piece of equipment ($CC_1(Q_1)$ or $ACC_1(Q_1)$) by escalating the known capital cost or average capital cost of a reference facility or piece of equipment ($CC_2(Q_2)$ or $ACC_2(Q_2)$), as shown below in Equations 4.11 and 4.12.

$$CC_1(Q_1) = CC_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{n_{Tot}} \tag{4.11}$$

$$ACC_1(Q_1) = ACC_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{\beta_{Tot}} \tag{4.12}$$

Lastly, as a preliminary cost estimation technique, the cost-to-capacity method is easy to apply. Nonetheless, the following considerations must be addressed before applying the method in order to obtain reasonable results:

1. The technology of the facility, or piece of equipment, for which the cost is being estimated must resemble the technology of the facility, or piece of equipment, for which the cost is known [138].
2. Although it has not been pointed out in previous studies, it must be known if the reference\historical cost, used in the cost-to-capacity method, includes accrued interest during construction or not. In other words, a particular output elasticity of capital cost might be valid for overnight cost escalations, but not for total capital costs (overnight cost + interest during construction) escalations.
3. Reference\historical costs ought to be adjusted to the relevant year, accounting for inflation [138].
4. The output elasticity of capital cost may vary over particular ranges of capacity, depending on the type of technology and, therefore, a representative output elasticity of capital cost must be used for particular cost estimations [138].

4.1. According to [137], in nuclear power plant cost escalations, the output elasticity of capital cost varies with capacity escalation ranges as follows:

Table 4.6: Relationship between Output Elasticity of Capital Cost and Capacity Escalation Ranges, in the nuclear sector.
Source: [137]

Capacity Escalation Ranges	$\mathbf{n_{Tot}}$
500 - 600 MWe	0.8
500 - 1,100 MWe	0.7
1,100 - 1,200 MWe	0.5

5. If the method is applied for entire facilities, rather than individual pieces of equipment, differences in location have to be considered. Locational cost adjustment factors may be necessary [138].

6. Output elasticities of capital cost can be determined with confidence only in stable technological, economic and regulatory environments [135].

4.2.3 The Cost-to-Capacity Method in the Nuclear Sector

Unfortunately, published cost data is not always clear regarding what is included in the cost [134]. Conventionally, published capital costs of power plants do not include the interest incurred during construction and only focus on the overnight cost [139]. Additionally, as it was previously highlighted, experts have found that a generic evaluation of financial costs is meaningless [129]. Consequently, in the nuclear sector, cost-size relationships are normally derived based on historical overnight costs, rather than total capital costs which consider overnight cost and interest incurred during construction. This is, in the nuclear sector, the Cost-to-Capacity method is applied by convention as follows (See Equations 4.13 and 4.14).

$$OC_1(Q_1) = OC_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{n_{oc}} \tag{4.13}$$

Or

$$AOC_1(Q_1) = AOC_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{n_{oc}-1} = AOC_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{\beta_{oc}} \tag{4.14}$$

Where the subscripts (1,2) stand for two different nuclear power plants and:

- $OC(Q)$: Overnight cost of a nuclear power plant, as a function of its capacity or output.

- $AOC(Q)$: Average overnight cost (or overnight cost per unit capacity) of a nuclear power plant as a function of its capacity or output.
- Q: Capacity or output of the corresponding nuclear power plant.
- n_{oc}: Output elasticity of overnight cost.
- β_{oc}: Output elasticity of average overnight cost.

In this context, the cost-size relationship of nuclear power plants has been studied by experts around the world since the early 1960s [129]. In fact, in an attempt to determine how the cost-size relationship of nuclear power plants was viewed by planners, economists and engineers; [140] made an extensive literature review and found 34 data sources that had been published or reported between 1965 and 1982. Nevertheless, [140] also found that only seven out of those 34 sources dealt with empirical data, while the rest were based on engineering estimates or personal judgement.

On one hand, the majority of engineering studies have estimated an output elasticity of overnight cost (n_{oc}) of 0.4 - 0.6 for nuclear power plants in the capacity ranges of 300 to 1300 MWe [129, 135]. On the other hand, by including the continually increasing regulatory costs of nuclear power plants and acknowledging the time value of money, the majority of econometric studies (e.g. [137, 141, 142, 143]) have found a weak economy of scale for nuclear with an output elasticity of overnight cost (n_{oc}) of 0.6 - 0.8. Furthermore, on a more neutral ground and more recently, the Organisation for Economic Co-operation and Development (OECD) and the Nuclear Energy Agency (NEA) have suggested an $n_{oc} = 0.4$ - 0.7 [144], while the IAEA proposed an $n_{oc} = 0.6$ for the escalation of overnight costs of nuclear power plants [145].

4.2.4 Average Overnight Cost of SMRs in a UK Scenario

As noted by [144]: "an important concern while analysing the economics of SMRs, is the lack of data regarding their construction cost and the differences between SMR projects". However, acknowledging that it is an order of magnitude estimation method, the Cost-to-Capacity method can be used to estimate the average overnight cost ($£/kWe$) of a representative 300 MWe Integral SMR. Later on, resembling previous SMR average overnight cost estimations (e.g. [130, 144, 145]), the preliminary estimation provided by the Cost-to-Capacity method (Equation 4.14) can be refined upon consideration of relevant correction factors such as: improved construction methods, design improvement, standardisation and mass production, and co-siting economies; as illustrated by

Equation 4.15 and Figure 4.1.

$$AOC_1(Q_1) = AOC_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{n_{oc}-1} \times CF_1 \times CF_2 \times \ldots \times CF_N \qquad (4.15)$$

Where CF_i are the correction factors that depend upon the situation assessed (e.g. First Of A Kind (FOAK), Next Of A Kind (NOAK), 1^{st} On A Site and Nth On A Site).

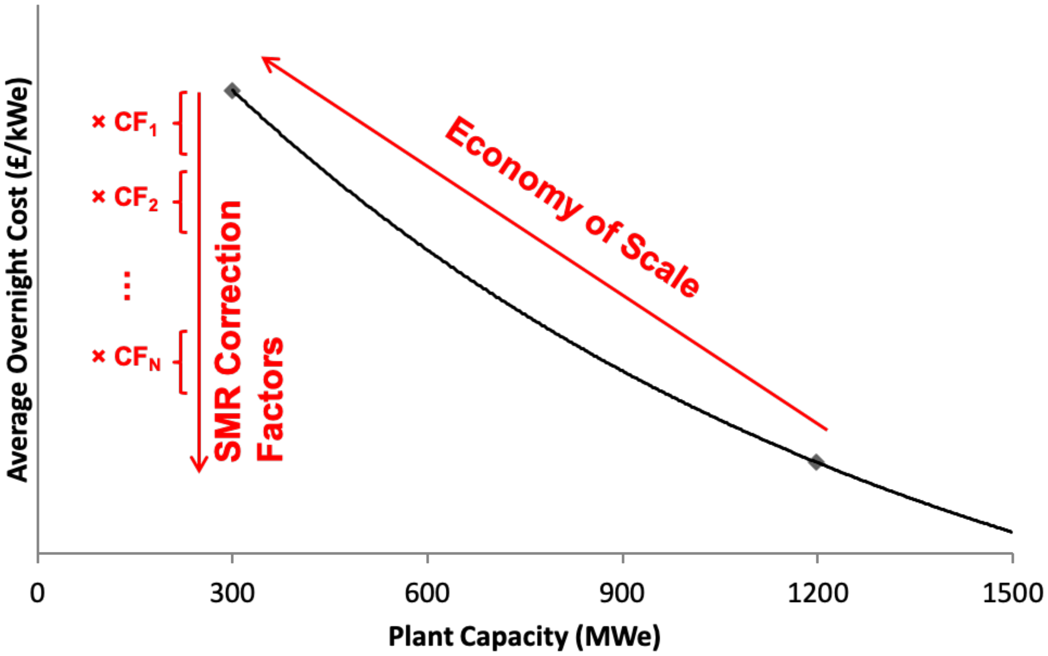

Figure 4.1: Schematic Representation of the Generic Cost-to-Capacity Method normally used to calculate the Average Overnight Cost of SMRs.

4.2.4.1 Reference Large Scale Nuclear Power Plant

As previously mentioned, the correct application of the Cost-to-Capacity method requires the usage of a reference plant with equivalent or similar technology to that of the plant for which the costs are being escalated. Consequently, in order to avoid the usage of locational cost adjustment factors and to reflect contemporary economic conditions, it would be desirable to use an integral PWR recently constructed and commissioned in the UK as the reference plant. In relation, on one hand, Rolls-Royce led the first 330 MWe integral reactor design during the 1980s and early 1990s, but it was never released to the market [146]. On the other hand, at the moment (2018), there are 15 operational civil nuclear reactors in the UK: 14 Advanced Gas-cooled Reactors (AGRs) and one 1198 MWe Pressurised Water Reactor (PWR) operated by EDF Energy Nuclear Generation Ltd. in Sizewell B, on the Suffolk coast [147, 148].

Given that the generic 300 MWe SMR that was chosen for this study is an Integral PWR, Sizewell B is naturally the best reference plant to be used in a cost escalation based on the application of the Cost-to-Capacity method, if only, as a first approximation. As a FOAK project in the UK, the construction of Sizewell B started in 1988, then the plant started operation in 1995 and its estimated decommissioning date is 2035, although EDF intends to extend its operational lifetime to 60 years [148, 149]. Furthermore, according to the UK's National Audit Office [150] and [139, 151], Sizewell B power station had an approximated overnight cost of £$3bn$ (or around 2,500 £$/kWe$), in 1996 money. As a result, according to the Bank of England inflation calculator [152], the £$3bn$ (1996 GBP) overnight cost of Sizewell B is equivalent to approximately £$5bn$[19] (or 4,500 £$/kWe$[20]) in today's money (2017 GBP), due to an averaged annual inflation rate of 2.8%. In this context, Sizewell B is a representative FOAK large reactor given that its overnight cost falls within the typical 4,200-5,200 £$/kWe$[21] overnight cost range of large scale nuclear, estimated by [153]. Finally, assuming that the overnight cost of Sizewell B was uniformly distributed among its 8 years construction period, the total size of investment (overnight cost + interest during construction) required for Sizewell B was approximately £$7bn$-£$8bn$[22] (or 5,600-7,000 £$/kWe$[23]) in today's money (2017 GBP), considering a 5-10% compounded annual interest rate, as recommended by [68] for a private sector utility in a regulated market.

4.2.4.2 Application of the Cost-to-Capacity Method - Preliminary Overnight Cost of a FOAK SMR

Based on the previously calculated overnight cost of Sizewell B (£$5bn$ in 2017 GBP), considering its output power capacity of 1198 MWe and assuming an output elasticity of overnight cost of n_{oc} = 0.4 - 0.8; the preliminary overnight cost of a generic FOAK 300 MWe Integral Pressurised Water Small Modular Reactor would be that shown in Table 4.7 and Table 4.8.

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[19] Figure rounded to billions.

[20] Figure rounded to hundreds.

[21] Figures originally presented in 2012 money. Converted to 2017 money upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.3% averaged annual inflation rate.

[22] Calculated using Equation A.1 (See Appendix A.1). Figures rounded to billions.

[23] Figures rounded to hundreds.

Table 4.7: Preliminary Overnight Cost of a FOAK 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. FOAK SMR **Overnight Cost (£) - Preliminary Estimation**			
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP)	5,353,585,657		
Cost-to-Capacity Factor	×0.57	×0.44	×0.33
Overnight Cost SMR (2017 GBP)	3,076,879,799	2,332,616,900	1,768,382,894

Table 4.8: Preliminary Average Overnight Cost of a FOAK 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. FOAK SMR **Average Overnight Cost (£/kWe) - Preliminary Estimation**			
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469		
Cost-to-Capacity Factor	×2.30	×1.74	×1.32
Overnight Cost SMR (2017 GBP/kWe)	10,256	7,775	5,895

4.2.4.3 Correction Factors and the Impact of a Reduced Construction Schedule

As illustrated by Tables 4.7 and 4.8, traditional techno-economic evaluations have shown that, in the nuclear sector, the average overnight cost per unit electricity decreases with increasing plant size or plant capacity [145]. In other words, the main factor negatively affecting the investment required for SMRs is the economy of scale displayed by nuclear power plants [144]. However, the investment analysis of SMRs versus Large Reactors (LRs) cannot rely entirely on cost-capacity relationships and economies of scale. In other words, cost escalation techniques as the Cost-to-Capacity method assume that SMRs and LRs are equal except for size, which in reality is not true [145]. This is, as shown previously in Equation 4.15, while economies of scale increase the average overnight cost of SMRs, other economic (or correction) factors may improve it: (1) improvement in construction methods, (2) design improvement, (3) standardisation and constructions in series / series production economies, (4) multiple units at a single site / co-siting economies, and (5) a reduced construction schedule.

Design Improvement

In the view of many electricity generation companies, the only way to minimise cost while maintaining quality is to make products simpler to manufacture. In relation, the simplification of nuclear power plant designs has led to a reduction of materials, efforts, costs and length of manufacture and/or construction. Moreover, not only existing reactor designs are being improved, but also entirely new plants that are less complex and rely more on passive safety systems are being designed (e.g. integral designs). For example, in the case of SMRs, its reduced size allows the introduction of passive safety features as a natural convection core [129].

On one hand, due to the reverse effect of economies of scale, SMRs might have an increased average overnight cost. On the other hand, some reactor vendors claim to keep the costs of Pressurised Water SMRs similar to those of large scale PWRs, upon creating an integral reactor design [129]. This is, reactor vendors estimate that the incorporation of size-specific features, that are not applicable to LRs, could reduce the overnight cost of near-term SMRs by at least 15% [144, 145]. Nonetheless, as stated by [129]: “so far no small reactor plant has been built that demonstrates the economic advantages of the new concepts, and all costs are based on paper studies which are likely to overstate the actual advantages achievable in practice”.

Improved Construction Methods

At first, the construction techniques of Nuclear Power Plants (NPPs) were based on the fossil power plant construction experience of industrialised countries. Nevertheless, considerable developments and improvements have been achieved since the first NPPs were built. In relation, many OECD member countries have developed multiple innovative construction techniques, to ensure the quality of construction and reduce the cost of NPPs [129]. Furthermore, a summary of the most important improved construction methods, that might result in cost savings, is presented in Table 4.9.

Throughout this study it has been assumed that a generic SMR would only benefit, without uncertainty, of improved modular construction techniques. Furthermore, the marginal 1.4-4% overnight cost reduction due to modularisation suggested by reference [129] is used in later sections to provide the reader with conservative order of magnitude cost estimations. Nevertheless, it is acknowledged that this 1.4-4% overnight cost reduction due to modularisation was most likely estimated for on-site modular construction and, therefore, it does not account for the benefits of construction in a factory setting. Consequently, the potential impact of this missing ‘factory-built factor’ on the economic performance of near term SMRs is later investigated in Subsection 5.3.1 in Chapter 5.

Table 4.9: Improved construction techniques that might lead to a cost reduction of NPPs.
Source: [129].

Construction Method	**Potential Cost Saving (% of overnight cost)**	**Basic Description**
Open top construction	2.4	Equipment is moved through the top of the reactor building, using large heavy lift cranes.
Modularisation	1.4 - 4.0	Modular construction.
Improved cabling and instrumentation & control	1.0	Application of computer technologies for the improvement of cable installation.
Formed pipe elbows and reduction in weld inspection	0.4	Elbow fittings deletion by forming bends within pipe lengths.
Sequencing of contractors	0.6 - 0.8	Effective co-ordination of contractors and integration within the construction sequence.

Standardisation and Construction in Series

In the view of [129], the greatest potential for overnight cost reduction of SMRs lies in utilising standardised plant designs and constructing standardised plants in series. Standardisation leads to benefits related to the consolidation of NPPs safety and the avoidance of FOAK effort. On one hand, the consolidation of NPPs safety arises from the adoption of proven approaches and the wider applicability of operation feedback. On the other hand, the standardisation of design, manufacturing, construction, licensing and operation approaches; reduces FOAK costs. As a result, overnight cost savings due to standardisation and construction in series are reported to range from 15% to 20%. However, it is also reported that the benefits of series production are achieved only when more than six units are implemented [129].

Construction of Multiple Units at a Single Site

The construction of several units at a single site provides opportunities for average overnight cost reductions. First, the construction of several units at a single site allows the sharing of land cost and site-licensing costs among multiple units. Later, craft teams can implement a phased construction scheme and roll various craft teams from one unit to the next. Similarly, multiple units benefit from the usage of common facilities like access roads, temporary work site buildings, administration and maintenance buildings, warehouses, radioactive waste building, etc. Consequently, multiple unit construction is reported to lead to an overnight cost reduction of approximately 15%, only applicable to subsequent units (not the First On A Site) [129]. Nevertheless, multiple reactors built using parallel construction would not benefit from co-siting economies, as this construction technique would eliminate the effects of learning from the previous units on-site.

Reduced Construction Schedule

Lengthy construction schedules expose Nuclear Power Plant(s) (NPP) to a variety of risks which translate into economic costs. Such risks include: increased interest during construction, escalation in equipment, material and labour costs, new licensing requirements, public opposition, political changes, etc. In particular, the length of the construction stage has a significant impact on the overall cost of NPPs due to the cost of financing (aka Interest During Construction (IDC)) [144]. In fact, the timing of a specific expenditure can add more than 25% to the total capital cost, due to the IDC. Consequently, a shorter construction period leads to earlier profits resulting from the start of commercial operation and, therefore, reduces the economic risks of a lengthy construction schedule [129].

According to reactor vendors' estimates, the construction stage of SMRs will be shorter than that of LRs [144]. On one hand, the construction schedules of LRs are typically assumed to be of 5-6 years [144, 145]. In relation, it must be noted that the reference plant used in this study (Sizewell B with a single FOAK 1198 MWe PWR) had a construction time of 8 years, whereas UK's newest nuclear power plant (Hinkley Point C) is expected to be constructed in the same amount of time and it will have a 3260 MWe twin unit UK-European Pressurised Water Reactor (UK-EPR) [154, 155, 156]. In other words, it is reasonable to assume that a NOAK LR could be built in about 5-6 years, if no delays are faced. On the other hand, reactor vendors' claim that water cooled SMRs (at a detailed design stage) will have a construction schedule of 3-4 years or less [128].

4.2.4.4 SMRs' Adjusted Average Overnight Cost

Following the conservative assumptions and correction factors listed in Table 4.10, the average overnight cost of a 300 MWe Integral Pressurised Water SMR was estimated, applying Equation 4.15, for three different scenarios: (1) FOAK SMR (See Table 4.11), (2) NOAK & First On A Site SMR (See Table 4.12), and (3) NOAK & Nth On A Site SMR (See Table 4.13). Moreover, it must be noted that the correction factors summarised in Table 4.10 already account for overnight cost reductions due to the potentially reduced construction schedule of SMRs. In contrast, the impact of a reduced construction schedule on the size of investment (overnight cost + IDC) required for SMRs is analysed in later sections (See Section 4.3).

Table 4.10: Conservative assumptions made for the application of an adjusted Cost-to-Capacity Generic Method.
Overnight Cost.

Cost-to-Capacity Method Corrections	**Assumed Average Overnight Cost Reduction**	**Correction Factor**
Design Improvement	15%	× .85
Modular Construction	1%	× .99
Construction in Series	15%	× .85
Co-siting	15%	× .85

Table 4.11: Adjusted Average Overnight Cost of a FOAK 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. FOAK SMR Average Overnight Cost (£/kWe) - Refined Estimation			
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469		
Cost-to-Capacity Factor	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85		
Modular Construction Correction Factor	× 0.99		
Cumulative Correction Factor	×1.93	×1.46	×1.11
Overnight Cost SMR (2017 GBP/kWe)	8,631	6,543	4,960

Table 4.12: Adjusted Average Overnight Cost of a NOAK & First On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. NOAK-First On A Site SMR Average Overnight Cost (£/kWe) - Refined Estimation			
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469		
Cost-to-Capacity Factor	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85		
Modular Construction Correction Factor	× 0.99		
Construction in Series Correction Factor	× 0.85		
Cumulative Correction Factor	×1.64	×1.24	×0.94
Overnight Cost SMR (2017 GBP/kWe)	7,336	5,562	4,216

Table 4.13: Adjusted Average Overnight Cost of a NOAK & Nth On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. NOAK-Nth On A Site SMR Average Overnight Cost (£/kWe) - Refined Estimation			
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469		
Cost-to-Capacity Factor	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85		
Modular Construction Correction Factor	× 0.99		
Construction in Series Correction Factor	× 0.85		
Co-Siting Correction Factor	× 0.85		
Cumulative Correction Factor	×1.40	×1.06	×0.80
Overnight Cost SMR (2017 GBP/kWe)	6,236	4,727	3,584

From Tables 4.11-4.13, depending on the scenario assessed and the extent of economies of scale, the average overnight cost (£/kWe) of 300 MWe Integral Pressurised Water SMRs could be equivalent to 80-193% of the average overnight cost (£/kWe) of ~1200 MWe FOAK Pressurised Water Large Reactors. What is more, in order to contextualise the results presented above, Figure 4.2 allows the comparison of the values presented in Table 4.11 with the typical overnight cost range of FOAK large scale nuclear in the UK, calculated by [153] and adjusted to 2017 prices by the author[24]. Similarly, Figure 4.3 shows how the values presented in Table 4.12 would differ from the typical overnight costs of NOAK large scale nuclear in the UK, published by [17] and adjusted to 2017 prices by the author of the present study[24]. Finally, although no representative historical record was found for the contextualisation of the values presented in Table 4.13, Figures 4.2 and 4.3 suggest that the SMRs that are closest to commercial operation are likely to have an average overnight cost (£/kWe) greater than that of large reactors, regardless of the scenario considered. Nevertheless, [17] estimated an overnight cost of 4,650-6,460[24] £/kWe for FOAK Pressurised Water SMRs and, therefore, this suggests that the weak and medium economies of scale scenarios (n_{oc}= 0.6 - 0.8, corresponding to the low and central estimate scenarios in Figure 4.2) are the ones that resemble the most a UK context. Consequently, focusing only on the low and central estimate scenarios, Figures 4.2 and 4.3 indicate that near term SMRs are likely to have a higher average overnight cost (£/kWe) than large reactors, but not as high as suggested by the high estimate scenarios.

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[24] Adjusted to 2017 prices upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.3% averaged annual inflation rate.

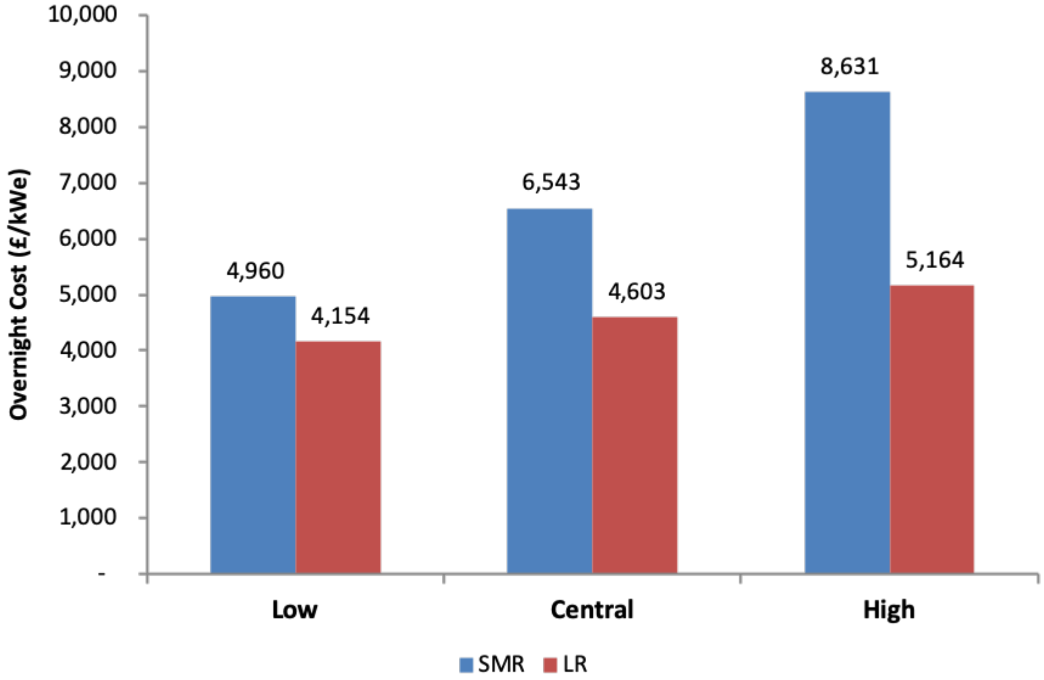

Figure 4.2: Low ($n_{oc} = 0.8$), Central ($n_{oc} = 0.6$) and High ($n_{oc} = 0.4$) Overnight Cost Estimates of FOAK SMRs and Typical Large Scale Nuclear FOAK Overnight Costs. Source for Large Scale Nuclear: [153].

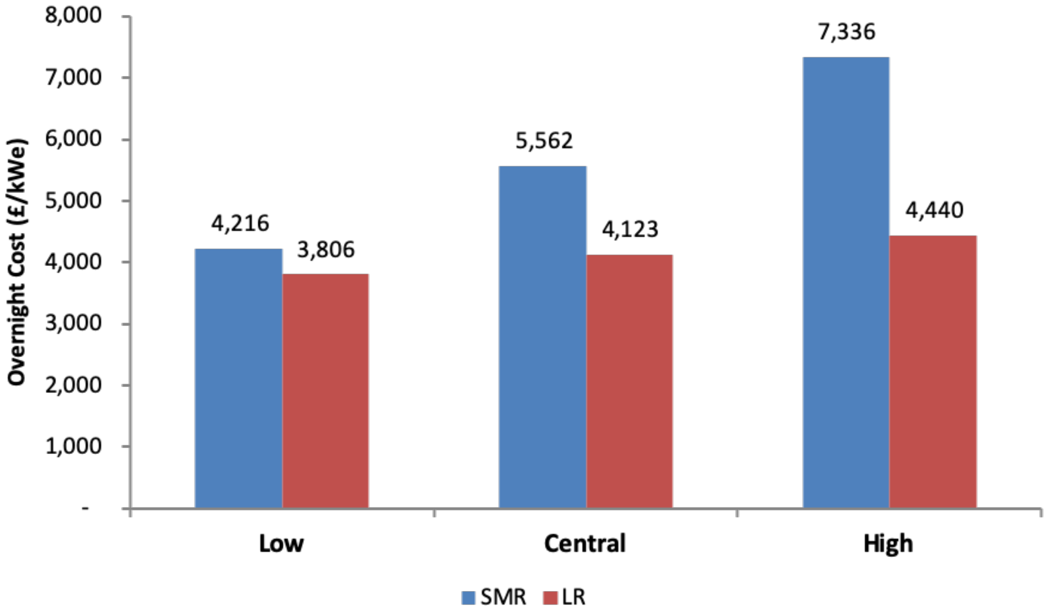

Figure 4.3: Low ($n_{oc} = 0.8$), Central ($n_{oc} = 0.6$) and High ($n_{oc} = 0.4$) Overnight Cost Estimates of NOAK-First On A Site SMRs and Typical Large Scale Nuclear NOAK-First On A Site Overnight Costs.
Source for Large Scale Nuclear: [17]

4.3 Size of Investment

In Section 4.2, the average overnight cost (£/kWe) of a 300 MWe Integral Pressurised Water SMR was calculated by escalating down the cost of the 1198 MWe PWR of Sizewell B. Later on, the preliminary average overnight cost of the representative SMR was refined upon the application of SMR specific correction factors. Furthermore, these overnight cost correction factors, only applicable to nuclear reactors, already account for the overnight cost reduction due to a reduced construction schedule. Nevertheless, a reduced construction period would not only decrease the overnight cost of SMRs, but also the cost of financing and, therefore, the total cost of investment of SMRs. Consequently, in order to analyse the impact of a potentially reduced construction schedule on the total size of investment (£/kWe) required for a representative 300 MWe Integral Pressurised Water SMR, it was assumed that the overnight costs presented in Tables 4.11-4.13 (See Subsection 4.2.4.4) would be evenly distributed among a 4 years construction period for FOAK SMRs and a 3 years construction period for NOAK SMRs. The results obtained are now presented in Tables 4.14 to 4.16, where Equation A.1 (See Appendix A.1) was applied considering 5-10% compounded annual interest rates, accordingly.

Table 4.14: Estimated Size of Investment of a FOAK 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. FOAK SMR Size of Investment (£/kWe)						
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469					
Cost-to-Capacity Factor	×2.30	×1.74	×1.32	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85					
Modular Construction Correction Factor	× 0.99					
Cumulative Correction Factor	×1.93	×1.46	×1.11	×1.93	×1.46	×1.11
Overnight Cost SMR (2017 GBP/kWe)	8,631	6,543	4,960	8,631	6,543	4,960
Interest rate (%)	5			10		
Interest During Construction SMR (2017 GBP/kWe)	1,134	860	652	2,384	1,808	1,370
Size of Investment SMR (2017 GBP/kWe)	9,765	7,403	5,612	11,015	8,351	6,331

Table 4.15: Estimated Size of Investment of a NOAK & First On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. NOAK-First On A Site SMR Size of Investment (£/kWe)						
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469					
Cost-to-Capacity Factor	×2.30	×1.74	×1.32	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85					
Modular Construction Correction Factor	× 0.99					
Design Improvement Correction Factor	× 0.85					
Construction in Series Correction Factor	× 0.85					
Cumulative Correction Factor	×1.64	×1.24	×0.94	×1.64	×1.24	×0.94
Overnight Cost SMR (2017 GBP/kWe)	7,336	5,562	4,216	7,336	5,562	4,216
Interest rate (%)	5			10		
Interest During Construction SMR (2017 GBP/kWe)	758	575	436	1,567	1,188	901
Size of Investment SMR (2017 GBP/kWe)	8,094	6,136	4,652	8,904	6,750	5,117

Table 4.16: Estimated Size of Investment of a NOAK & Nth On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. NOAK-Nth On A Site SMR Size of Investment (£/kWe)						
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469					
Cost-to-Capacity Factor	×2.30	×1.74	×1.32	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85					
Modular Construction Correction Factor	× 0.99					
Design Improvement Correction Factor	× 0.85					
Construction in Series Correction Factor	× 0.85					
Co-Siting Correction Factor	× 0.85					
Cumulative Correction Factor	×1.40	×1.06	×0.80	×1.40	×1.06	×0.80
Overnight Cost SMR (2017 GBP/kWe)	6,236	4,727	3,584	6,236	4,727	3,584
Interest rate (%)	5			10		
Interest During Construction SMR (2017 GBP/kWe)	645	489	370	1,332	1,010	766
Size of Investment SMR (2017 GBP/kWe)	6,880	5,216	3,954	7,568	5,737	4,350

Moreover, with the intention of putting the above presented results in context, the size of investment (£/kWe) of typical large scale FOAK and NOAK nuclear power plants was calculated for low, central and high cost scenarios upon utilisation of Table 4.17, Equation A.1 (See Appendix A.1), considering 5-10% compounded annual interest rates and assuming that the corresponding overnight costs were evenly distributed among the respective construction periods. On one hand, drawing on the experience acquired with Sizewell B and Hinkley Point C, an 8 years construction period was assumed for FOAK large reactors. On the other hand, following common assumptions, a 6 years construction period was used for the calculation of the size of investment of typical NOAK large reactors. Later on, the estimated sizes of investment of typical FOAK and NOAK large reactors were matched with their SMR counterparts: n_{oc}= 0.8 with low estimates of LRs, n_{oc}= 0.6 with central estimates of LRs and n_{oc}= 0.4 with high estimates of LRs. As a result, it was found that, except for the case of weak economies of scale, the SMRs that are closest to commercial operation might struggle to compete economically with LRs even after considering the theoretical unique potential cost reductions of SMRs. Nonetheless, as it was previously noted in Subsection 4.2.4.4, the weak and medium economies of scale scenarios seem to resemble the most a UK context and, therefore, the previously stated conclusion implies that near term SMRs do have chances to compete economically against LRs in a UK scenario.

From Figures 4.4 to 4.7, the size of investment (£/kWe) required for near term SMRs could be anywhere between 5% smaller and 50% greater than that required for LRs, depending on the scenario and interest rate considered. Particularly, in a UK scenario (weak and medium economies of scale), the size of investment of near term SMRs could oscillate between 5% smaller and 30% greater than that of LRs. In relation, the impact of a possibly shorter construction schedule of SMRs was also analysed in [145], by calculating the total capital investment (overnight cost + IDC) required for a LR and for an SMR with construction durations of 5 and 3 years respectively, under the same conditions. As a result, [145] also found that the shorter construction time required for an SMR could result in a 5%[25] saving in total investment (£/kWe) [26].

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[25] For a 5% interest rate.

[26] [145] does not specify a particular scenario or if this calculation was done for FOAK or NOAK reactors.

Table 4.17: Typical Overnight Costs of FOAK and NOAK Large Scale Nuclear in a UK context. Figures adjusted to 2017 prices. Sources: [17, 153]

Large Scale Nuclear Overnight Cost[27] **(£/kWe)**		
SCENARIO	FOAK	NOAK
Low	4,154	3,806
Central	4,603	4,123
High	5,164	4,440

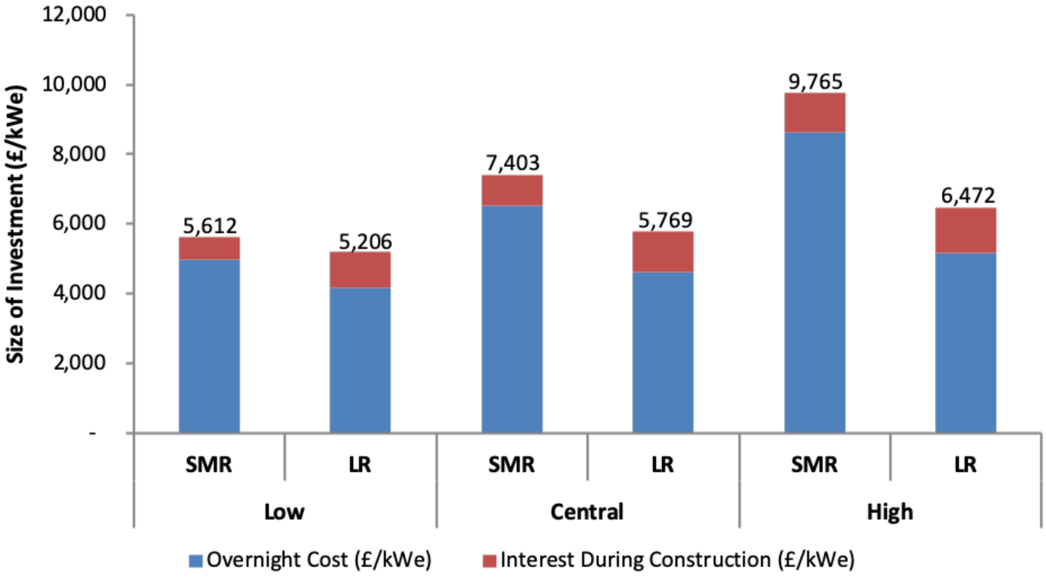

Figure 4.4: Low ($n_{oc} = 0.8$), Central ($n_{oc} = 0.6$) and High ($n_{oc} = 0.4$) Size of Investment Estimates of FOAK SMRs and Typical FOAK Large Scale Nuclear, considering a 5% compounded annual interest rate.

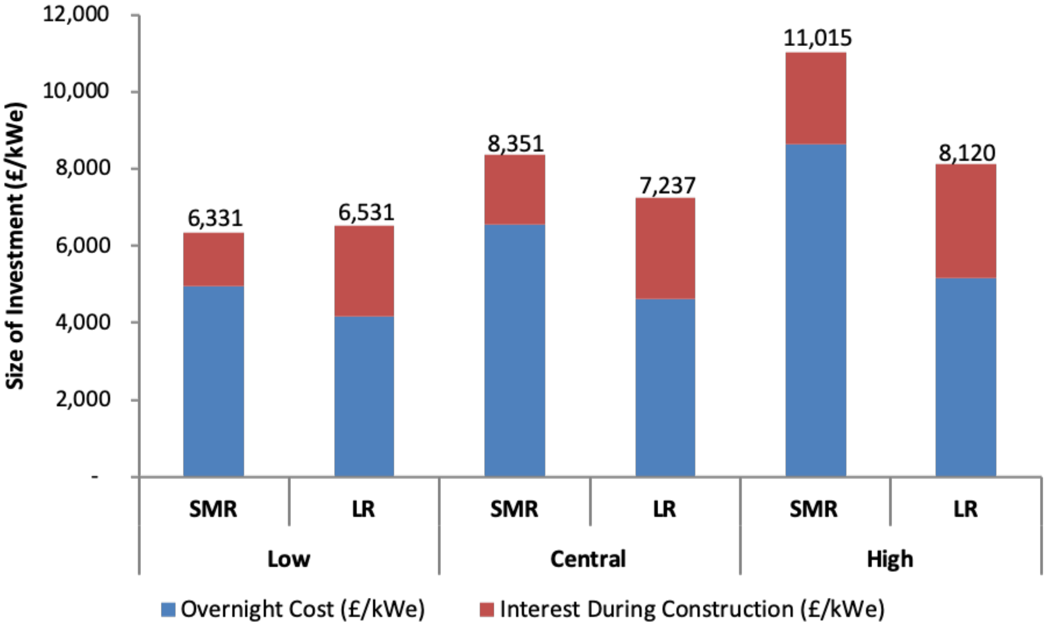

Figure 4.5: Low ($n_{oc} = 0.8$), Central ($n_{oc} = 0.6$) and High ($n_{oc} = 0.4$) Size of Investment Estimates of FOAK SMRs and Typical FOAK Large Scale Nuclear, considering a 10% compounded annual interest rate.

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[27] Figures adjusted to 2017 prices upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.3% averaged annual inflation rate. Originally presented in 2012 prices by [17, 153].

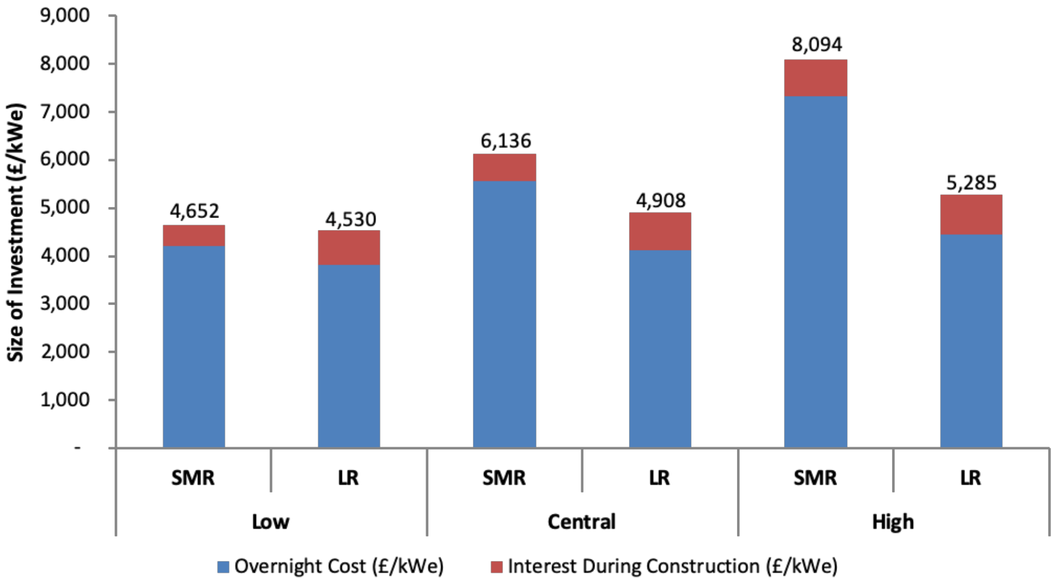

Figure 4.6: Low ($n_{oc} = 0.8$), Central ($n_{oc} = 0.6$) and High ($n_{oc} = 0.4$) Size of Investment Estimates of NOAK-First On A Site SMRs and Typical NOAK-First On A Site Large Scale Nuclear, considering a 5% compounded annual interest rate.

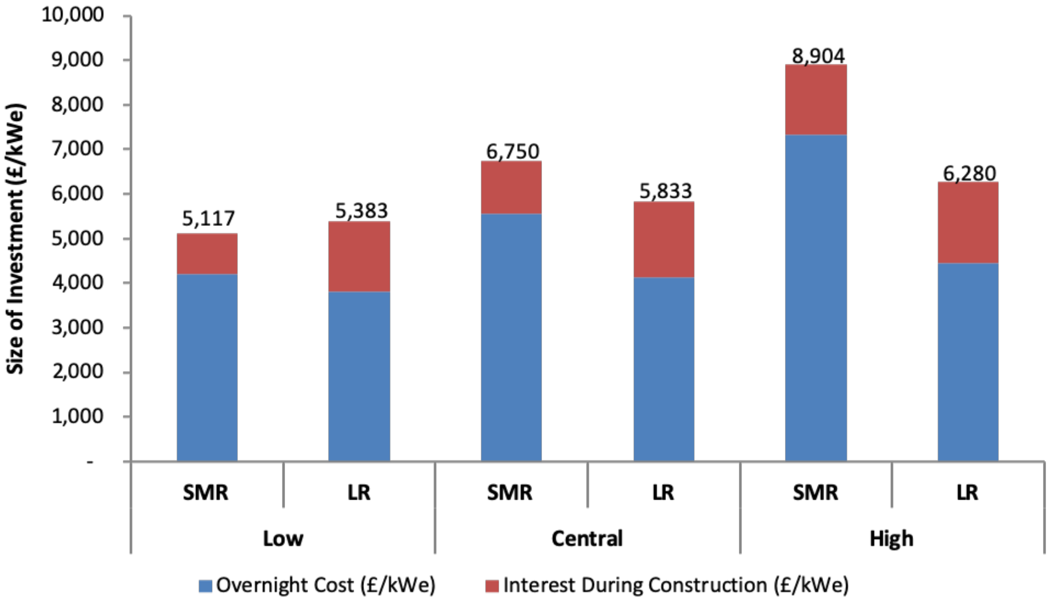

Figure 4.7: Low ($n_{oc} = 0.8$), Central ($n_{oc} = 0.6$) and High ($n_{oc} = 0.4$) Size of Investment Estimates of NOAK-First On A Site SMRs and Typical NOAK-First On A Site Large Scale Nuclear, considering a 10% compounded annual interest rate.

In comparison, by the end of an 8 years construction period, the UK-EPR being built at Hinkley Point C (UK) is likely to account for a 7,055 $£/kWe$ investment [154, 155, 156], which would fall within the 5,769-7,232 $£/kWe$ central investment range estimated in this study for FOAK LRs. In contrast, with construction periods of 17 years, the EPRs being constructed at Olkiluoto-3 (Finland) and Flamanville-3 (France) might represent a 4,849 $£/kWe$ and a 9,979 $£/kWe$ investment respectively

[157, 158, 159, 160, 161, 162], both of which would fall beyond the limits of the low and high investment ranges suggested by Figures 4.4 and 4.5 for FOAK LRs. However, it is not clear if the total cost estimated for Olkiluoto-3 ($\sim$£7.8bn [157]) includes the extra interest paid during construction due to its numerous delays. Consequently, the construction periods assumed for LRs, the typical large reactor overnight cost figures presented in Table 4.17 and the sizes of investment estimated in this study for large scale nuclear (Figures 4.4 - 4.7) reflect accurately a UK scenario, but need to be adjusted if the analysis is expanded to other European nations[28].

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[28] Hinkley Point C (UK): 3260 MWe twin unit UK-EPR with a total cost of £23bn [156].
Olkiluoto-3 (Finland): 1600 MWe EPR with a total cost of $\sim$£7.8bn [157].
Flamanville-3 (France): 1650 MWe EPR with a total cost of $\sim$£16.5bn [161].

4.3.1 Test Case - Multiple (4) SMRs vs. Single LR - Size of Investment

When comparing the economic competitiveness of SMRs vs. LRs, the test case of 4 SMRs vs. 1 LR is normally presented, probably due to the fact that 4 SMRs are expected to have around the same capacity of 1 LR. In consequence, in order to compare the results presented above with those of previous studies, the size of investment test case of 4 SMRs vs. 1 LR is presented next. Moreover, previous economic analyses focusing on this test case (e.g. [144, 145]) do not specify which scenario was considered (e.g. FOAK or NOAK). However, as the results presented in this report show, different scenarios may lead to different conclusions. Consequently, in this case, the following scenarios were studied:

Table 4.18: Scenarios Considered for the 4 SMRs vs. 1 LR Test Case - Size of Investment

Scenario A
1 FOAK + 3 NOAK-Nth On A Site SMRs vs. 1 FOAK LR
Scenario B
1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs vs. 1 NOAK-1st On A Site LR

Lastly, resembling previous studies and for the sake of clarity, the following assumptions were made:

- **Output Elasticity of Overnight Cost:** $n_{oc} = 0.6$.
- **Average Overnight Cost of SMRs (See Tables 4.14-4.16):**
  FOAK = 6,543 $£/kWe$.
  NOAK-1st On A Site=5,562 $£/kWe$.
  NOAK-Nth On A Site = 4,727 $£/kWe$.
- **Central Overnight Cost Estimates of Large Reactors (See Table 4.17):**
  FOAK = 4,603 $£/kWe$.
  NOAK = 4,123 $£/kWe$.
- **Interest Rate:** 5%.
- **Discount Rate:** 5%.
- **Construction Period:**
  FOAK SMRs = 4 years.
  NOAK SMRs = 3 years.

FOAK Large Reactor = 8 years.

NOAK Large Reactor = 6 years.

- **Start of Operation:** The start of operation date of the large reactor and of the first SMR are assumed to coincide.
- **Construction Schedule SMRs:** The first construction year of a subsequent SMR is assumed to match the second construction year of a previous SMR.

As a result, as shown in Figure 4.8, in Scenario A it was found that 4 SMRs (1 FOAK + 3 NOAK-Nth On A Site) might have an average overnight cost 13% greater than FOAK LRs, but a size of investment ($£/kWe$) 3% smaller than FOAK LRs. In contrast, in the case of Scenario B, results suggest that 4 SMRs (1 NOAK-1st On A Site + 3 NOAK-Nth On A Site) could have an average overnight cost 20% greater than NOAK LRs and a size of investment ($£/kWe$) 4% greater than NOAK LRs.

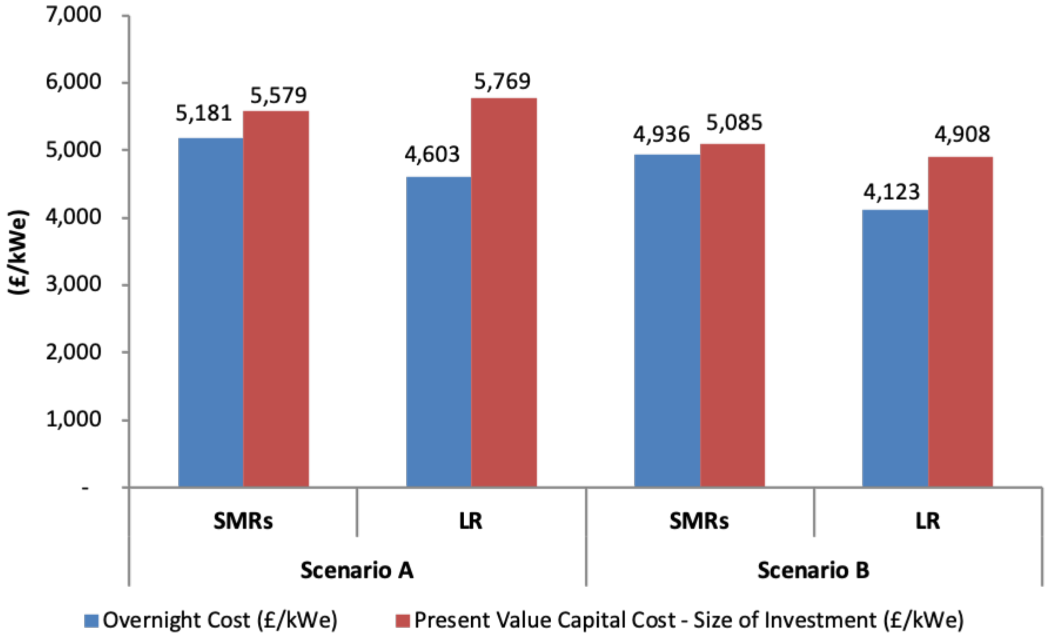

Figure 4.8: Test Case: 4 SMRs vs. 1 LR - Size of Investment.
Scenario A - 1 FOAK + 3 NOAK-Nth On A Site SMRs vs. 1 FOAK LR.
Scenario B - 1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs vs. 1 NOAK-1st On A Site LR.

On one hand, while [144] did not compare average overnight costs, [145] found that SMRs could have an average overnight cost 16% greater than that of large reactors. On the other hand, for the size of investment ($£/kWe$) comparison, [144] estimated that 4 SMRs would have an investment cost 10-22% greater than a single LR and [145] estimated that it would only be 4% greater (as in Scenario B of this study). In relation, small or big differences between the economic analyses presented in this study and those presented in other studies are likely to be attributable to differences between the assumed construction schedules and scenarios. Consequently, the results presented in this study suggest that while a single SMR could struggle to compete economically with LRs (See Figures 4.4-4.7), multiple SMRs might be able to compete economically with LRs, upon selecting a convenient construction schedule and matching the output power capacity of LRs. Similarly, results confirm that different scenarios (e.g. FOAK, NOAK, UK specific, etc.) can lead to different conclusions regarding the economic competitiveness of SMRs.

4.4 Operation and Maintenance (O&M) Cost

Apart from operation and maintenance, O&M costs include administration, material supplies, licence fees and salaries of personnel [163]. At the same time, O&M costs are divided into fixed (or irrespective of the level of plant operation) and variable costs [79]. In any case, altogether, O&M costs are a major component of the LCOE (see Subsection 3.3.1.1). In relation, although it is generally assumed that they account for approximately 20% of the LCOE this proportion has historically decreased due to information technologies and learning factors [135, 164]. In fact, lately, the LCOE breakdown of FOAK PWRs has become: 75% capital cost, 12.5% fixed O&M, 3.75% variable O&M, 6.25% fuel and 2.5% decommissioning [165].

4.4.1 O&M Cost of Nuclear Power Plants and Economies of Scale

As highlighted by [166], cost estimations for SMRs are in early stages of development and limited detailed information is in the public domain. In other words, at the time of this analysis, SMR O&M cost estimates have a significant amount of uncertainty. On one hand, due to a stronger reliance on passive safety systems, SMR designers often claim that the O&M cost of SMRs could be lower than that of large reactors [128, 144, 167]. On the other hand, cost reduction studies (e.g. [168]) expect the first SMRs to have higher O&M costs than large reactors due to most staffing costs being independent of the reactor capacity.

Fortunately, although it is not the only factor, economies of scale is the main factor influencing nuclear O&M costs [169]. As noted by [130], [170] demonstrated that the annual nonfuel O&M costs of light water PWRs and Boiling Water Reactors (BWRs) follow economies of scale, within the ~300-1300 MWe range. In fact, the output elasticity of total O&M cost (n_{OM}, See Subsection 4.2.1.5) has been estimated to be within the 0.6-0.7 range [169, 170]. Therefore, it is possible to make a preliminary O&M cost estimation for SMRs upon application of the Cost-to-Capacity method, previously discussed in Subsection 4.2.3. Later on, the preliminary SMR O&M cost estimation can be refined upon consideration of possible correction factors (e.g. passive safety systems, operational learning, co-siting and a potentially longer refuelling schedule) as illustrated by Equation 4.16.

$$AO\&M_1(Q_1) = AO\&M_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{n_{OM}-1} \times CF_1 \times CF_2 \times \ldots \times CF_N \tag{4.16}$$

Where CF_i are the correction factors that depend upon the situation assessed (e.g. FOAK, NOAK, 1^{st} On A Site and Nth On A Site) and:

- $AO\&M(Q)$: Average O&M cost (or O&M cost per unit capacity) of a nuclear power plant as a function of its capacity or output.
- Q: Capacity or output of the corresponding nuclear power plant.
- n_{OM}: Output elasticity of O&M cost.

4.4.2 Average O&M Cost of SMRs in a UK Scenario

4.4.2.1 Application of the Cost-to-Capacity Method - Preliminary O&M Cost of a FOAK SMR

Resembling the methodology previously followed to calculate the average overnight cost of a representative SMR in a UK scenario, the average O&M cost (fixed+variable) of a 300 MWe Integral Pressurised Water SMR was estimated assuming economies of scale and using Sizewell B (1198 MWe) as the reference large scale nuclear power plant. First, the lifetime discounted O&M cost (£/kWe) of Sizewell B was calculated upon consideration of the LCOE breakdown of large scale PWRs, presented earlier in this section, and the Size of Investment that was required for Sizewell B (5,600-7,000 £/kWe, see Subsection 4.2.4.1). As a result, it was estimated that the lifetime discounted average O&M cost of Sizewell B is likely to be within the 1,214-1,522 £/kWe range, with a central estimate of 1,368 £/kWe (in 2017 GBP). Moreover, considering a 60 years operational lifetime and 5-10% discount rates, the central estimate was undiscounted to a 4,130-7,486 £/kWe range. Later on, the upper limit of the possible undiscounted O&M cost range of Sizewell B (7,486 £/kWe) was selected as the most feasible due to its similarity with the 7,452 £/kWe[29] undiscounted O&M cost estimated by [165] for FOAK large scale PWRs. Finally, the Cost-to-Capacity method was applied considering an output elasticity of total O&M cost of n_{OM}=0.6-0.7. The results obtained are now presented in Table 4.19, where discounted values were also calculated taking into account: 5-10% discount rates, the typical 60 years operational lifetime expected for SMRs and assuming that O&M costs were evenly distributed among the operational lifetime of SMRs.

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[29] Figure originally presented in 2014 money. Converted to 2017 money upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.1% averaged annual inflation rate.

Table 4.19: Preliminary Average O&M Cost of a FOAK 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. FOAK SMR **Average O&M Cost (£/kWe) - Preliminary Estimation**						
Output Elasticity of O&M Cost (n_{OM})	0.6	0.65	0.7	0.6	0.65	0.7
Undiscounted O&M Cost of Reference Plant (2017 GBP/kWe)	7,486					
Cost-to-Capacity Factor	×1.74	×1.62	×1.51	×1.74	×1.62	×1.51
Undiscounted O&M Cost SMR (2017 GBP/kWe)	13,026	12,155	11,342	13,026	12,155	11,342
Discount rate (%)	5			10		
Discounted O&M Cost SMR (2017 GBP/kWe)	4,315	4,026	3,757	2,380	2,221	2,072

4.4.2.2 Correction Factors

As it was previously mentioned, the economy of scale factor is not the only O&M cost driver of SMRs [169]. Therefore, the preliminary O&M cost of a representative SMR, that was calculated in the previous section, has to be refined upon consideration of other factors influencing the O&M costs of SMRs. In other words, the Cost-to-Capacity method relies on the assumption that SMRs and LRs are equal except for size, which is not the case. Consequently, other economic or correction factors (e.g. passive safety systems, operational learning, co-siting and a potentially longer refuelling schedule) may improve the high O&M costs of SMRs that are predicted by economies of scale.

Passive Safety Systems

SMR vendors and designers often indicate that SMRs will have lower O&M costs than large reactors due to a stronger reliance on passive safety features (e.g. heat removal by natural circulation) [144]. By eliminating or reducing tanks, valves and pumps; passive mechanisms contribute to the simplification of SMR systems and components [171]. As a result, SMR vendors and designers (e.g. [172]) assume that the elimination of sensitive and maintenance-intensive components will definitely lead to lower O&M costs. However, this potential O&M cost reduction ignores the fact that O&M costs are particularly influenced by regulatory requirements (e.g. augmented in-service inspection, additional fire protection features, enhanced operator training, etc.). Following the Fukushima nuclear accident, there was an international response which culminated in a major review of nuclear safety. As a result, the UK nuclear industry subsequently implemented improvements such as the installation of super-articulated control rods and a seismically qualified nitrogen injection plant at Hinkley Point B and Hunterston B in order to enhance nuclear safety [173]. Moreover, particularly in the case of integral designs, reactor vendors still have to demonstrate that the reduced size of SMRs won't make routine maintenance more difficult. In consequence, up to date, the potential O&M cost reduction due to passive safety systems remains speculative and, therefore, its validity and magnitude are still unknown.

Operational Learning

SMRs are likely to facilitate the standardisation of design, operations and the supply chain. At the same time, a steeper learning curve than that of large reactors might be achievable. Therefore, operational learning may lead to an improved capacity factor and reduced variable O&M costs for SMRs. However, accumulated experience shows that it takes several years to optimise a reactor system. Initially, nuclear reactors start with low capacity factors and then, with time, improve to capacity factors of over 85% [168].

On one hand, large scale nuclear power plants can operate with capacity factors of over 90% in years without refuelling outages [80]. Nevertheless, capacity factors may change from one time period to the next due to external factors like changes in fuel prices or base load requirements, as indicated in Subsection 3.3.2.1. For example, in the case of Sizewell B, the capacity factor in 1996 was 81.3%, 100% in 2015 and 83.9% in 2017, with a lifetime cumulative capacity factor of 83.7% calculated up to year 2017 [174]. As a result, a standard capacity factor of 85-90% is normally assumed by convention [80, 153, 166].

On the other hand, a potential 5-10% capacity factor increase, in comparison with large reactors, is considered a conservative estimate for SMRs. These accelerated improvements in SMR capacity factors are a consequence of higher operating times (aka reactor years) than large reactors for the same power output [168]. In relation, although it is uncertain what capacity factors will SMRs achieve, reactor vendors indicate that SMRs will be capable of delivering capacity factors of 95% or more [126, 168]. As a result, operational learning leading to an improved capacity factor, has been estimated to reduce variable O&M costs by 2-3% [168]. Similarly, a further analysis made for this research project suggests that a 2-3% reduction of variable O&M costs would result in a 0.5-0.7% reduction of total O&M costs (fixed+variable costs).

Co-Siting

The construction of several units on a single site could not only reduce the overnight cost of SMRs (See Subsection 4.2.4.3), but also it could lead to lower O&M costs for SMRs. Co-siting of multiple reactors could facilitate the specialisation of operating engineering labour and could also allow sharing of staff and activities [168, 169]. In relation, [169] found that during the years 1981-1990 the O&M cost saving due to co-siting was close to 20-22% of total O&M costs. However, [169] suggests that after 1990 the impact of co-siting on O&M costs decreased to a 15% saving on total O&M costs.

Longer Refuelling Schedule

Nuclear plants do their planned maintenance and inspection of critical components during plant outage for refuelling, in order to maximise the plant availability. In relation, some authors (e.g. [168, 169]) suggest that SMRs could have longer refuelling intervals than large reactors. Particularly, [169] suggests that this could lead to a 2-5% O&M cost reduction. Nevertheless, excluding the AREVA SMR which is unlikely to be constructed in the near future, only 30% of the Pressurised Water SMR designs previously presented in Tables 4.1 and 4.2 are expected to have longer refuelling periods (36-48 months) than large scale PWRs (18-24 months), as shown below in Table 4.20.

Table 4.20: Typical refuelling intervals of near term Pressurised Water SMRs.

Reactor	**Electrical Capacity** (MWe)	**Fuel Cycle Length (months)**
NuScale SMR [175, 176, 177, 178]	50-60	24
B&W mPower SMR [179]	180	48
Westinghouse SMR [180]	225	24
ACP100 [181]	100	24
SMART [126]	100	36
UK SMR [127]	400-450	18-24
Fixed Bed Nuclear Reactor [126]	72	25
Integrated Modular Waste Reactor [126]	350	26
VBER-300 [126]	325	24
International Reactor Innovative and Secure [128]	335	30-48

Moreover, [168] argues that although SMRs could have longer refuelling intervals, this would not necessarily reduce O&M costs because there are planned inspections and maintenance that are required more often than every 4-5 years. These planned inspections and maintenance could result in dedicated shutdowns or the extension of sensitive inspections for SMRs with long refuelling intervals, nullifying possible O&M cost reductions due to a longer refuelling interval. Similarly, based on the SMR designs included in Table 4.20, the Pressurised Water SMRs that are closest to commercial operation are expected to have similar burnups (~50-60 GWd/tU), higher fuel enrichment (<5%) and higher capacity factors (90-95%), but smaller specific power densities

(∼20-30 $MWth/tU$) than conventional large scale PWRs, probably due to the poorer neutron economy of a small reactor core [144]. This is, for non-PWR technologies working in the thermal neutron spectrum, the longer refuelling intervals assumption could be true, but for Pressurised Water SMRs the higher capacity factors might compensate the lower specific power densities of SMRs and leave the refuelling intervals just as those of large reactors. In consequence, it was decided that a generic 300 MWe Integral Pressurised Water SMR might not necessarily have a longer refuelling period than large reactors and, therefore, a potential O&M cost reduction due to longer refuelling intervals was not considered for the calculations presented in this work.

4.4.2.3 SMRs' Adjusted Average O&M Cost

Following the assumptions and correction factors listed in Table 4.21, the average O&M cost of a 300 MWe Integral Pressurised Water SMR was estimated, applying Equation 4.16, for three different scenarios: (1) FOAK SMR (See Table 4.22), (2) NOAK & First On A Site SMR (See Table 4.23), and (3) NOAK & Nth On A Site SMR (See Table 4.24). Moreover, as in the case of the SMR preliminary O&M cost estimation, discounted values are also presented for 5-10% discount rates and an operational lifetime of 60 years. Lastly, it must be noted that the FOAK SMR scenario (Table 4.22) shows no variation with respect to the preliminary O&M cost estimation (Table 4.19) due to the fact that no validated correction factors were found to be applicable to this scenario.

Table 4.21: Assumptions made for the application of an adjusted Cost-to-Capacity Generic Method.
O&M Cost.

Cost-to-Capacity Method Corrections	**Assumed Average O&M Cost Reduction**	**Correction Factor**
Operational Learning	0.5%	× .995
Co-Siting	15%	× .85

Table 4.22: Adjusted Average O&M Cost of a FOAK 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. FOAK SMR Average O&M Cost (£/kWe) - Refined Estimation						
Output Elasticity of O&M Cost (n_{OM})	0.6	0.65	0.7	0.6	0.65	0.7
Undiscounted O&M Cost of Reference Plant (2017 GBP/kWe)	7,486					
Cost-to-Capacity Factor	×1.74	×1.62	×1.51	×1.74	×1.62	×1.51
Undiscounted O&M Cost SMR (2017 GBP/kWe)	13,026	12,155	11,342	13,026	12,155	11,342
Discount rate (%)	5			10		
Discounted O&M Cost SMR (2017 GBP/kWe)	4,315	4,026	3,757	2,380	2,221	2,072

Table 4.23: Adjusted Average O&M Cost of a NOAK & First On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. NOAK-First On A Site SMR Average O&M Cost (£/kWe) - Refined Estimation						
Output Elasticity of O&M Cost (n_{OM})	0.6	0.65	0.7	0.6	0.65	0.7
Undiscounted O&M Cost of Reference Plant (2017 GBP/kWe)	7,486					
Cost-to-Capacity Factor	×1.74	×1.62	×1.51	×1.74	×1.62	×1.51
Operational Learning Correction Factor	× 0.995					
Cumulative Correction Factor	×1.73	×1.62	×1.51	×1.73	×1.62	×1.51
Undiscounted O&M Cost SMR (2017 GBP/kWe)	12,961	12,094	11,285	12,961	12,094	11,285
Discount rate (%)	5			10		
Discounted O&M Cost SMR (2017 GBP/kWe)	4,293	4,006	3,738	2,368	2,210	2,062

Table 4.24: Adjusted Average O&M Cost of a NOAK & Nth On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK Large Reactor vs. NOAK-Nth On A Site SMR Average O&M Cost (£/kWe) - Refined Estimation						
Output Elasticity of O&M Cost (n_{OM})	0.6	0.65	0.7	0.6	0.65	0.7
Undiscounted O&M Cost of Reference Plant (2017 GBP/kWe)	7,486					
Cost-to-Capacity Factor	×1.74	×1.62	×1.51	×1.74	×1.62	×1.51
Operational Learning Correction Factor	× 0.995					
Co-Siting Correction Factor	× 0.85					
Cumulative Correction Factor	×1.47	×1.37	×1.28	×1.47	×1.37	×1.28
Undiscounted O&M Cost SMR (2017 GBP/kWe)	11,017	10,280	9,592	11,017	10,280	9,592
Discount rate (%)	5			10		
Discounted O&M Cost SMR (2017 GBP/kWe)	3,649	3,405	3,178	2,013	1,878	1,753

From Tables 4.22-4.24, depending on the scenario assessed and the extent of economies of scale, the average O&M cost of a 300 MWe Integral Pressurised Water SMR could be equivalent to 128-174% of the average O&M cost of ∼1200 MWe FOAK large scale PWRs. Furthermore, in order to contextualise the results presented above, the central (n_{OM}=0.65) O&M costs shown in Tables 4.22 and 4.23 were compared with the central O&M costs estimated by [153] for FOAK and NOAK large scale PWRs[30], considering a 10% discount rate and a 60 years operational lifetime (See Figures 4.9 and 4.10). As a result, it was found that irrespectively of the scenario assessed near term SMRs could, almost certainly, have significantly higher O&M costs than their

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[30] Figures originally presented in 2012 money. Converted to 2017 money upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.3% averaged annual inflation rate.

large scale counterparts. Nonetheless, it must be acknowledged that possible O&M cost reductions that require further investigation (e.g. passive safety systems) could reduce the gap between the O&M costs of SMRs and large reactors.

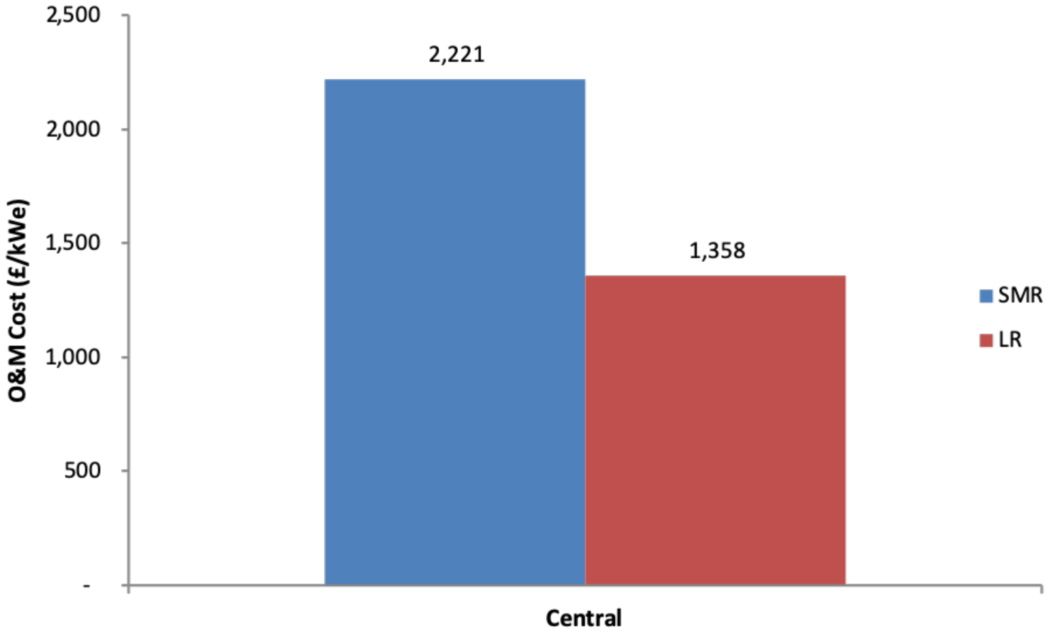

Figure 4.9: Central ($n_{OM} = 0.65$) O&M Discounted Cost Estimates of FOAK SMRs and Typical FOAK Large Scale Nuclear considering a 10% discount rate.
Source for Large Scale Nuclear: [153].

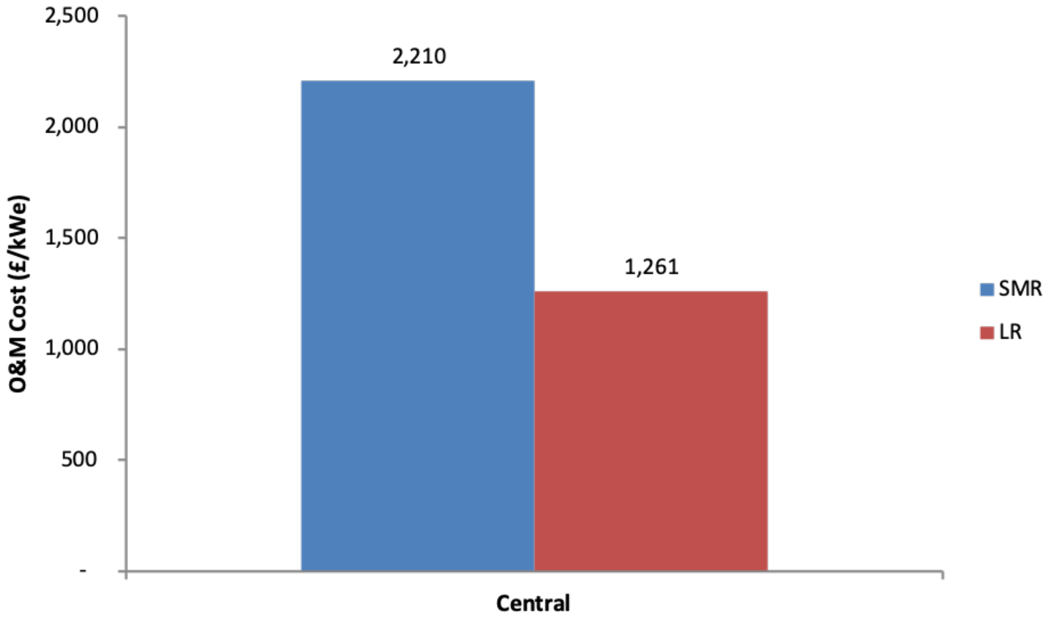

Figure 4.10: Central ($n_{OM} = 0.65$) O&M Discounted Cost Estimates of NOAK-First On A Site SMRs and Typical NOAK-First On A Site Large Scale Nuclear, considering a 10% discount rate.
Source for Large Scale Nuclear: [153].

4.4.3 Test Case - Multiple (4) SMRs vs. Single LR - O&M Cost

As previously introduced in Subsection 4.3.1, the test case of 4 SMRs vs. 1 LR is normally presented in economic analyses due to the fact that 4 SMRs are expected to have around the same capacity of 1 LR. Moreover, this test case is typically limited to size of investment comparisons. Nonetheless, the O&M test case of 4 SMRs vs. 1 LR is presented below in order to expand the current level of understanding of multiple SMR economics. In relation, the corresponding calculations were done considering central O&M estimates and the following scenarios (See Table 4.25):

Table 4.25: Scenarios Considered for the 4 SMRs vs. 1 LR Test Case - O&M Cost.

Scenario A
1 FOAK + 3 NOAK-Nth On A Site SMRs vs. 1 FOAK LR
Scenario B
1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs vs. 1 NOAK-1st On A Site LR

Moreover, due to the reduced data availability regarding discounted O&M costs of large reactors, the analysis of the test case was limited to discounted values considering a 10% discount rate. Similarly, the following assumptions were made:

- **Output Elasticity of O&M Cost:** $n_{OM} = 0.65$.
- **Central Undiscounted O&M Cost SMRs (See Tables 4.22-4.24):**
  FOAK = 12,155 £$/kWe$.
  NOAK-1st On A Site= 12,094 £$/kWe$.
  NOAK-Nth On A Site = 10,280 £$/kWe$.
- **Central Discounted O&M Cost Estimates of Large Reactors (From [153]):**
  FOAK = 1,358 £$/kWe$[31].
  NOAK = 1,261 £$/kWe$[31].
- **Discount Rate:** 10%.
- **Construction Period:**
  FOAK SMRs = 4 years.
  NOAK SMRs = 3 years.
  FOAK Large Reactor = 8 years.
  NOAK Large Reactor = 6 years.

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[31] Figure adjusted to 2017 prices upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.3% averaged annual inflation rate. Originally presented in 2012 prices by [153].

- **Start of Operation:** The start of operation date of the large reactor and of the first SMR are assumed to coincide.
- **Construction Schedule SMRs:** The first construction year of a subsequent SMR is assumed to match the second construction year of a previous SMR.
- **Operational Lifetime:**
  SMRs = 60 years.
  Large Reactor = 60 years.

As illustrated by Figure 4.11, in Scenario A it was found that 4 SMRs (1 FOAK + 3 NOAK-Nth On A Site) might have an average O&M cost 35% greater than FOAK LRs. Similarly, the results of Scenario B indicate that 4 SMRs (1 NOAK-1st On A Site + 3 NOAK-Nth On A Site) could have an average O&M cost 36% greater than NOAK LRs.

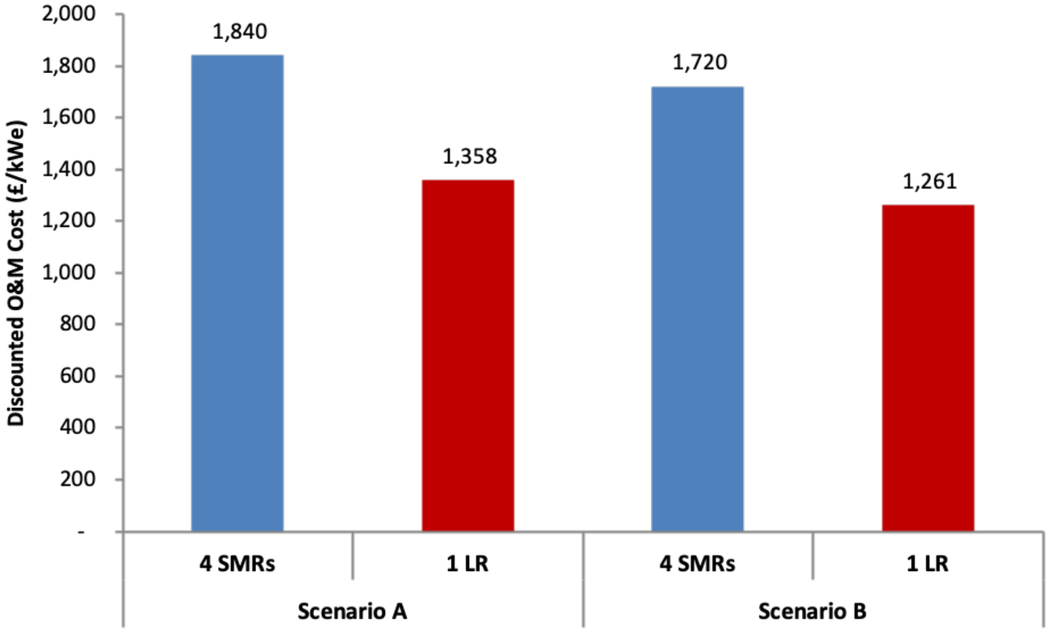

Figure 4.11: Test Case: 4 SMRs vs. 1 LR - Discounted O&M Cost. Scenario A - 1 FOAK + 3 NOAK-Nth On A Site SMRs vs. 1 FOAK LR. Scenario B - 1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs vs. 1 NOAK-1st On A Site LR.

From Tables 4.22-4.24 and Figure 4.11, if no further O&M cost reductions are demonstrated (e.g. passive safety systems), SMR O&M cost estimates suggest that SMRs will hardly compete against large reactors on a one to one basis. Nevertheless, if one considers multiple SMRs, then the gap between the O&M costs of SMRs and large reactors could be reduced almost by half. Finally, no previous studies were found to analyse the 4 SMRs vs. 1 LR test case for O&M costs, as they normally focus on overnight costs and sizes of investment. Therefore, the results here presented can be used as a benchmark for future works.

4.5 Fuel Cost

In the nuclear industry, fuel costs include all the cash outflows due to the nuclear fuel cycle material and services, except for the reactor operation costs. In relation, the term 'nuclear fuel cycle' makes reference to the progression of nuclear fuel through a series of different stages before (front end), during (reactor operations) and after (back end) its use for the production of electricity from nuclear reactions [182]. The front end of the fuel cycle includes the following four steps: uranium purchase (from mining to milling), conversion to uranium hexafluoride, enrichment and fuel fabrication [145]. Later on, the at-reactor stage covers the use of fuel assemblies in the reactor core for around 2-4 years, depending on the corresponding refuelling scheme [145, 168]. Nonetheless, it is worth to mention that, the at-reactor costs are normally regarded as operational costs rather than fuel cycle costs [183]. Finally, for appropriate fuel cost evaluations, two back end options are normally considered: open and closed fuel cycle [145]. However, multiple recycling of LWR uranium has never been done successfully and it is very unlikely to be achievable or economic. Moreover, recalling Section 4.1, the UK definition of SMRs is limited to ~300 MWe LWRs and, as a result, anything that can operate on a closed fuel cycle won't be a UK SMR. In consequence, throughout this study only the open fuel cycle back end option was investigated. The open fuel cycle back end covers spent fuel transport & storage, encapsulation and disposal (See Figure 4.12) [183].

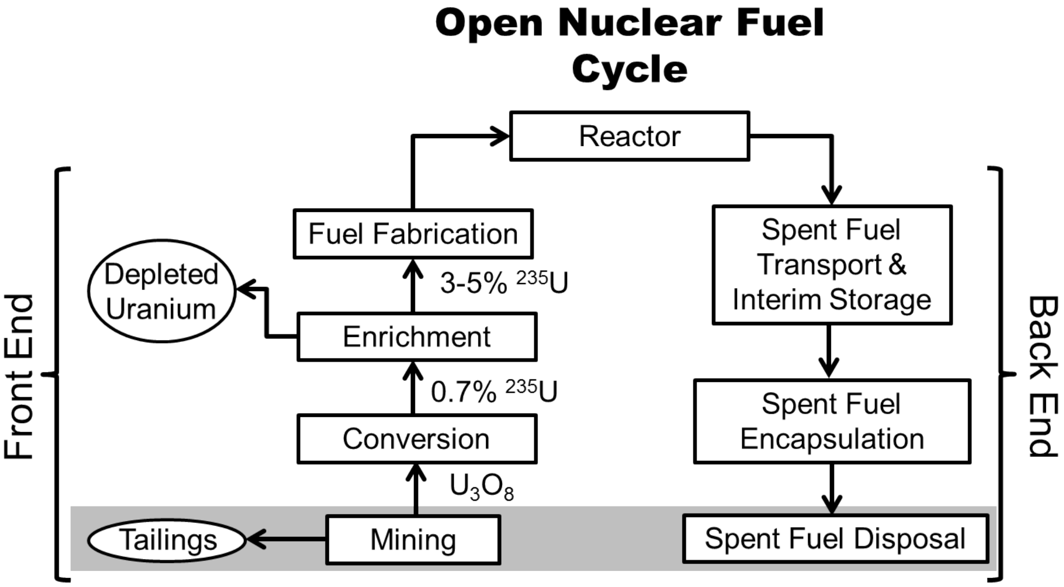

Figure 4.12: Schematic Representation of Open Nuclear Fuel Cycle Stages.
Source: [183, 184].

4.5.1 Average Fuel Cost of SMRs in a UK Scenario

Considering the reactor core specifications of near term SMRs (See Table 4.28), paying special attention to ~300 MWe SMR designs, the reactor core specifications of a representative 300 MWe Integral Pressurised Water SMR were inferred (See Table 4.29). Later on, once the main features of the reactor core of a representative 300 MWe Integral Pressurised Water SMR were identified, the open nuclear fuel cycle prices (on a per kgU or SWU basis) were investigated. As a result, [183] was found to be the only source that quotes the cost of every open fuel cycle stage (See Table 4.26) and also provides the methodology to calculate the Separative Work Units (SWUs) necessary for the production of a certain amount of uranium enriched to a particular level (See Appendix E.1). However, upon analysing historical front end fuel cycle costs, published by UxC [185], it was determined that uranium purchase, conversion and enrichment prices are highly volatile and depend on the length of the contracts. Consequently, Table 4.26 was modified by constructing low (minimum), central (average), and high (maximum) front end fuel cycle cost scenarios[32] based on UxC historical front end fuel cycle costs[33], utilising a US inflation calculator [186] in order to present all figures (front and back end) in 2017 prices and converting them to 2017 GBP using the HM Revenue & Customs exchange rate for 2017 (1 GBP = 1.282692 USD [187])(See Table 4.27). Moreover, while the rise in uranium purchase prices due to the Fukushima nuclear accident was considered, the rise in prices due to the 2007 economic crisis was not considered for the construction of the three, perviously mentioned, front end fuel cycle cost scenarios. Although the 2007 economic crisis caused uranium purchase prices to increase dramatically, this price increment was a result of market speculation and those high prices remained only for a few days.

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[32] Nuclear fuel fabrication price was assumed to remain equal to the price originally proposed by [183]. This quantity was only modified due to the consideration of inflation.

[33] Only the period 1988-2019 for uranium purchase price and the period 1995-2019 for uranium conversion and enrichment prices are available and were considered.

Table 4.26: PWR Fuel Cycle Unit Prices, in Early 1991 Money Value. Source: [183].

Component	**Reference Unit Price**
Uranium Purchase	50 USD/kgU escalation 1.2% per annum.
Conversion	8 USD/kgU
Enrichment	110 USD/SWU
Fabrication	275 USD/kgU
Open Fuel Cycle	
Spent Fuel Transport & Storage	230 USD/kgU^{34}
Encapsulation & Disposal	610 USD/kgU^{35}

Table 4.27: Assumed PWR Fuel Cycle Unit Prices, in 2017 Money Value.

Component	**Reference Unit Price**		
	Low	Central	High
Uranium Purchase (GBP/kgU)	19.75	63	173.39
	+1.2% per annum.		
Conversion (GBP/kgU)	2.73	6.73	10.85
Enrichment (GBP/SWU)	28.21	97.26	142.53
Fabrication (GBP/kgU)	386		
Open Fuel Cycle			
Spent Fuel Transport & Storage	323 GBP/kgU^{34}		
Encapsulation & Disposal	856 GBP/kgU^{35}		

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[34] Payable on delivery to the interim storage site and includes the price of transport.

[35] Payable on delivery to the encapsulation and disposal site.

Table 4.28: Reactor Core of Near Term Pressurised Water SMRs.

Reactor	**Thermal Capacity** ($MWth$)	**Electrical Capacity** (MWe)	**Fuel Cycle Length (months) / Refuelling Scheme**	**Burnup** (GWd/tU)	**Fuel Type**	**Array Type**	**No. of Fuel Assemblies**	**Total Fuel Inventory** (tU)	**Enrichment** (%)	**Total Natural Uranium Inventory** (tU_{nat})
NuScale SMR [175, 176, 177, 178]	160-200	50-60	24 / 3 Batch	62	Industry Standard UO_2 with Gadolinium Oxide.	17×17	37	9.22	<4.95	-
B&W mPower SMR [16, 179]	530	180	48 / 1 Batch	35	Industry Standard UO_2.	17×17	69	<20	<5	-
Westinghouse SMR [16, 180, 188]	800	225	24 / 40% of Core	>62	Industry Standard UO_2.	17×17	89	-	<5	-

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Table 4.28 – Continued from previous page.

Reactor	**Thermal Capacity** ($MWth$)	**Electrical Capacity** (MWe)	**Fuel Cycle Length (months) / Refuelling Scheme**	**Burnup** (GWd/tU)	**Fuel Type**	**Array Type**	**No. of Fuel Assemblies**	**Total Fuel Inventory** (tU)	**Enrichment (%)**	**Total Natural Uranium Inventory** (tU_{nat})
ACP100 [16, 181]	310	100	24 / NA	52	Chinese Nuclear Fuel CF2 shortened assembly.	17×17	57	-	4.2	-
SMART [126, 188]	330	100	36 / 2 Batch	36.1	Industry Standard UO_2.	17×17	57	14.3	4.8	-
UK SMR [127]	1200-1350	400-450	18-24 / NA	55-60	Industry Standard UO_2.	17×17	121	-	4.95	-
Fixed Bed Nuclear Reactor [126]	218	72	25 / NA	15.3	CERMET (Pebble Bed).	-	-	10.5	5	-

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Reactor	**Thermal Capacity** ($MWth$)	**Electrical Capacity** (MWe)	**Fuel Cycle Length (months) / Refuelling Scheme**	**Burnup** (GWd/tU)	**Fuel Type**	**Array Type**	**No. of Fuel Assemblies**	**Total Fuel Inventory** (tU)	**Enrichment (%)**	**Total Natural Uranium Inventory** (tU_{nat})
Integrated Modular Waste Reactor [126]	1000	350	26 / 3 Batch	46	Industry Standard UO_2.	21×21	97	51.8	4.8	-
VBER-300 [126, 188]	917	325	24 / 3 Batch	47	Industry Standard UO_2.	Hexagonal.	85	38	4.95	420
International Reactor Innovative and Secure [128, 188]	1000	335	30-48 / 2 Batch & 1 Batch	60	Sintered Ceramic UO_2 / MOX pellets.	17×17	89	48.5	4.95	403

Table 4.29: Assumed Reactor Core of Near Term 300 MWe Integral Pressurised Water SMRs.

Reactor	**Thermal Capacity** ($MWth$)	**Electrical Capacity** (MWe)	**Fuel Cycle Length (months) / Refuelling Scheme**	**Burnup** (GWd/tU)	**Fuel Type**	**Array Type**	**No. of Fuel Assemblies**	**Total Fuel Inventory** (tU)	**Enrichment** (%)	**Total Natural Uranium Inventory** (tU_{nat})
Representative 300 MWe SMRs	1000	300	24 / 3 Batch - 48 / 1 Batch	50	Industry Standard UO_2.	17×17	90	46	4.9	436

Furthermore, assuming the reactor core specifications shown in Table 4.29, the nuclear fuel cycle costs shown in Table 4.27, the payments schedule suggested by [183] (See Table 4.30) and a 60 years operational lifetime; the average fuel cost ($£/kWe$) of a 300 MWe Integral Pressurised Water SMR was calculated for 1 or 3 batch refuelling schemes and 5-10% discount rates (See Tables 4.31 - 4.32). In relation, results suggest that a 3-batch refuelling scheme with 24 months refuelling intervals is likely to be more cost-efficient than a single batch refuelling scheme with 48 months refuelling intervals.

Moreover, in order to size the results presented below and due to the resemblance between refuelling schemes, the possible central fuel cost of near term SMRs with: open fuel cycles, three batch refuelling schemes and 10% discount rates; was compared with the central fuel cost estimated by [153] for large scale PWRs[36] (See Figure 4.13). In comparison, [153] excluded the so-called 'Waste Fund' from the fuel cost of large scale reactors and, therefore, the encapsulation and disposal cost was subtracted from the fuel cost of the corresponding SMRs for a fair comparison. As a result, it was found that near term SMRs are likely to have higher average fuel costs (as much as 80% higher) than their large scale counterparts. Moreover, judging by the main features of large scale PWRs around the world, reported in [189, 190], near term SMRs could use twice as much fuel as large scale PWRs (on a per MWe basis) and could require fuel to be enriched up to 40% more. As suggested by [144], this might have to do with the poorer neutron economy of a smaller reactor core. Nevertheless, in any case, due to the unknown fuel cycle prices assumed by [153] and the uncertainty of future nuclear fuel cycle prices, the results presented here must only be considered as indicative figures.

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[36] Figures originally presented in 2012 money. Converted to 2017 money upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.3% averaged annual inflation rate.

Table 4.30: PWR Fuel Cycle Data.
Source: [183].

Item	**Reference**
Feed Assay	0.71%
Tails Assay	0.25%
Lead time (relative to fuel loading date) for:	
Uranium Purchase	24 months[37]
Conversion	18 months[37]
Enrichment	12 months[37]
Fabrication	6 months[37]
Lag time (relative to spent fuel discharge date) for:	
Spent Fuel Transport	5 years
Open Fuel Cycle[38]	
Interim Storage	5 years
Encapsulation & Disposal	40 years

Table 4.31: Average Fuel Cost of a FOAK/NOAK 300 MWe Integral Pressurised Water Small Modular Reactor. Open Fuel Cycle and 1-Batch Refuelling Scheme.

FOAK/NOAK SMR Average Fuel Cost (£/kWe) - Open Fuel Cycle - 1 Batch Refuelling Scheme						
Fuel Cycle Cost Scenario	Low	Central	High	Low	Central	High
Uranium Purchase	606	1,935	5,325	606	1,935	5,325
Conversion	59	147	237	59	147	237
Enrichment	457	1,577	2,311	457	1,577	2,311
Fabrication	887	887	887	887	887	887
Spent Fuel Transport and Storage	742	742	742	742	742	742
Encapsulation and Disposal	1,969	1,969	1,969	1,969	1,969	1,969
Undiscounted Fuel Cost SMR (2017 GBP/kWe)	4,721	7,256	11,470	4,721	7,256	11,470
Discount rate (%)	5			10		
Uranium Purchase	204	652	1,793	123	393	1,081
Conversion	23	58	93	15	37	60
Enrichment	173	595	872	109	375	550
Fabrication	332	332	332	205	205	205
Spent Fuel Transport and Storage	170	170	170	66	66	66
Encapsulation and Disposal	82	82	82	6	6	6
Discounted Fuel Cost SMR (2017 GBP/kWe)	984	1,888	3,342	524	1,082	1,968

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[37] For initial fuel, 6 months are added.

[38] Including 5 years storage at reactor followed by 35 years storage at interim storage facilities.

Table 4.32: Average Fuel Cost of a FOAK/NOAK 300 MWe Integral Pressurised Water Small Modular Reactor. Open Fuel Cycle and 3-Batch Refuelling Scheme.

FOAK/NOAK SMR **Average Fuel Cost (£/kWe) - Open Fuel Cycle - 3 Batch Refuelling Scheme**						
Fuel Cycle Cost Scenario	Low	Central	High	Low	Central	High
Uranium Purchase	428	1,365	3,758	428	1,365	3,758
Conversion	42	104	168	42	104	168
Enrichment	325	1,121	1,643	325	1,121	1,643
Fabrication	631	631	631	631	631	631
Spent Fuel Transport and Storage	528	528	528	528	528	528
Encapsulation and Disposal	1,400	1,400	1,400	1,400	1,400	1,400
Undiscounted Fuel Cost SMR (2017 GBP/kWe**)**	3,354	5,150	8,128	3,354	5,150	8,128
Discount rate (%)	5			10		
Uranium Purchase	153	487	1,340	100	318	876
Conversion	18	44	71	12	31	49
Enrichment	132	454	665	90	310	454
Fabrication	252	252	252	168	168	168
Spent Fuel Transport and Storage	121	121	121	49	49	49
Encapsulation and Disposal	58	58	58	5	5	5
Discounted Fuel Cost SMR (2017 GBP/kWe**)**	733	1,415	2,506	423	880	1,601

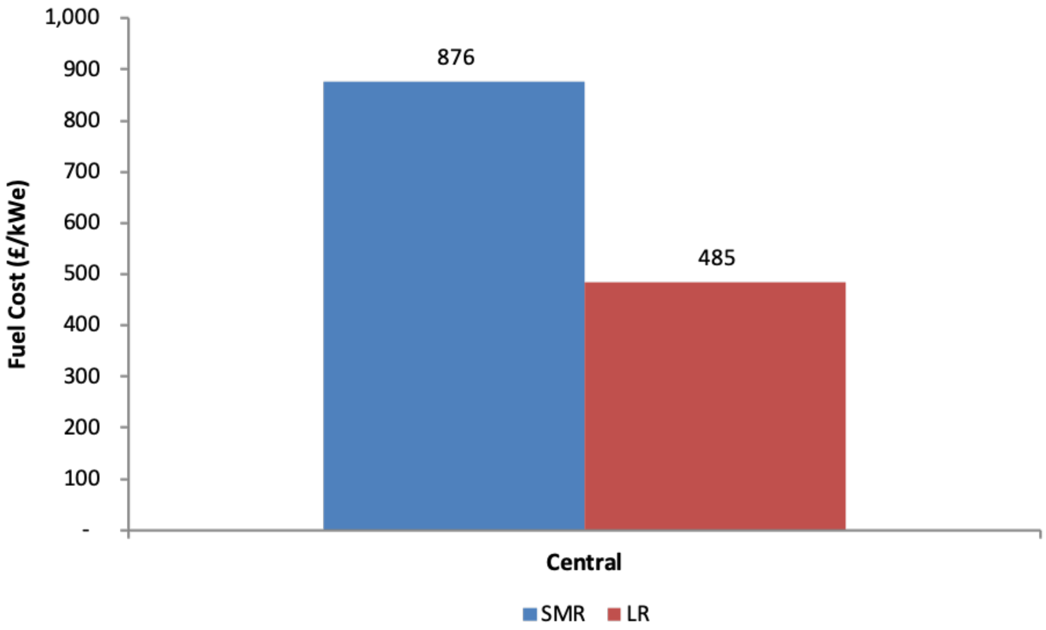

Figure 4.13: Central Fuel Discounted Cost estimates of FOAK/NOAK SMRs with a 3-batch refuelling scheme and Typical FOAK/NOAK Large Scale Nuclear, considering a 10% discount rate.
Source for Large Scale Nuclear: [153].

4.5.2 Test Case - Multiple (4) SMRs vs. Single LR - Fuel Cost

As in the case of O&M costs, no previous studies were found to analyse the 4 SMRs vs. 1 LR test case for fuel costs. The 4 SMRs vs. 1 LR test case is normally reserved only for size of investment comparisons. Nonetheless, in order to provide a wider view of the economics of SMRs, the test case of 4 SMRs vs. 1 LR is presented next, for central fuel cost estimates, considering the following scenarios (See Table 4.33):

Table 4.33: Scenarios Considered for the 4 SMRs vs. 1 LR Test Case - Central Fuel Cost.

Scenario A
1 FOAK + 3 NOAK SMRs vs. 1 FOAK / NOAK LR
Scenario B
4 NOAK SMRs vs. 1 FOAK / NOAK LR

Moreover, in line with the 4 SMRs vs. 1 LR O&M cost test case, the following assumptions were made for the 4 SMRs vs. 1 LR fuel cost test case:

- **Average Fuel Cycle Costs SMRs:** Central estimates, see Table 4.27.
- **Central Discounted Fuel Cost Estimates of Large Reactors (From [153]):** FOAK & NOAK = 485 $£/kWe$[39].
- **Fuel-related Payments Schedule:** See Table 4.30.
- **Reactor Core Features of SMRs:** See Table 4.29.
- **Refuelling Scheme of SMRs:** 3-Batch refuelling, every 24 months.
- **Fuel Cycle Option (SMRs & LRs):** Open Fuel Cycle.
- **Discount Rate:** 10%.
- **Construction Period:**
  FOAK SMRs = 4 years.
  NOAK SMRs = 3 years.
  FOAK Large Reactor = 8 years.
  NOAK Large Reactor = 6 years.
- **Start of Operation:** The start of operation date of the large reactor and of the first SMR are assumed to coincide.

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[39] Figure adjusted to 2017 prices upon utilisation of the Bank of England Inflation Calculator [152], which considered a 2.3% averaged annual inflation rate. Originally presented in 2012 prices by [153].

- **Construction Schedule SMRs:** The first construction year of a subsequent SMR is assumed to match the second construction year of a previous SMR.
- **Operational Lifetime:**
  SMRs = 60 years.
  Large Reactor = 60 years.

As illustrated by Figure 4.14, if the economic analysis was limited to fuel costs, multiple SMRs could have a better chance to compete economically against large reactors than single SMRs. On one hand, in Scenario A, results suggest that 4 SMRs (1 FOAK + 3 NOAK) could have an average fuel cost 69% greater than LRs. On the other hand, in Scenario B it was found that 4 SMRs (4 NOAK) could have an average fuel cost 56% greater than LRs. In other words, from Figures 4.13 and 4.14, near term SMRs are likely to have significantly higher fuel costs (at least 50% higher fuel costs) than their large scale counterparts regardless of possible co-siting benefits.

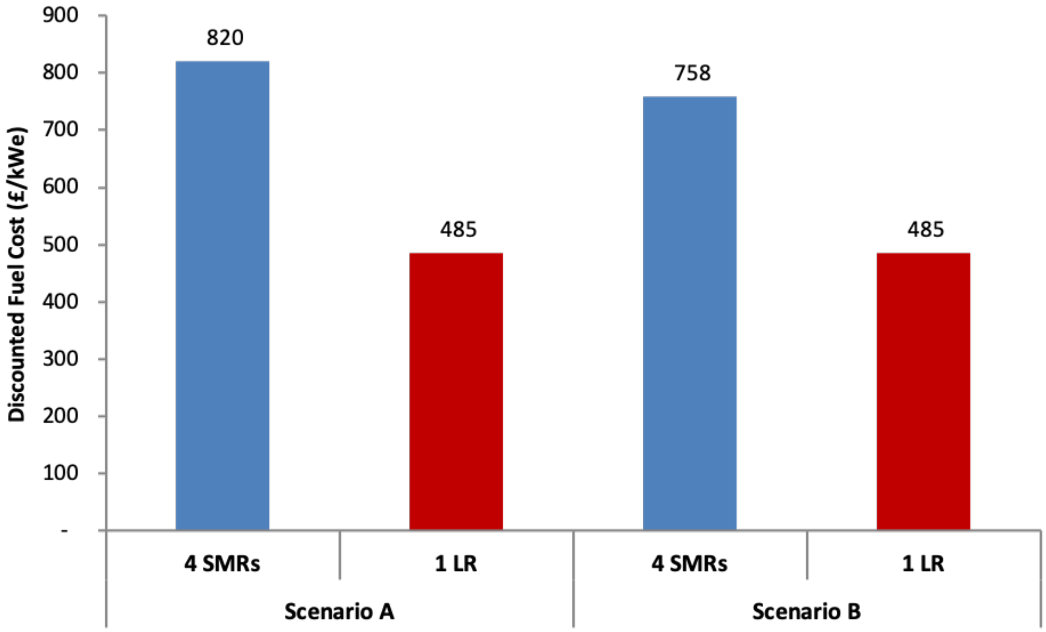

Figure 4.14: Test Case: 4 SMRs vs. 1 LR - Discounted Fuel Cost.
Scenario A - 1 FOAK + 3 NOAK SMRs vs. 1 FOAK / NOAK LR.
Scenario B - 4 NOAK SMRs vs. 1 FOAK / NOAK LR.
Source for Large Scale Nuclear: [153].

4.6 Decommissioning Cost

On one hand, early nuclear power plants used to operate for about 30 years. On the other hand, as indicated in Subsections 3.4.3.1, 3.5.2.1 and 4.2.4.1, modern nuclear power plants have an operational lifetime of 40-60 years. At the end of their operational lifetimes, nuclear power plants have to be decommissioned in order to make the sites available for other purposes [12]. In a broad sense, the term 'decommissioning' considers all the technical and management actions required for the cessation of operation and withdrawal from service of a nuclear power plant. Moreover, these actions include some or all of the following activities: dismantling, decontamination, demolition of building, remediation of contaminated ground and waste disposal [191].

Furthermore, according to [191], the two major components of nuclear decommissioning cost are (i) dismantling and (ii) waste treatment and disposal, approximately one fourth and one third respectively. Similarly, although their share is smaller, there are three other significant decommissioning cost drivers (around 10% each): (1) security, survey and maintenance, (2) site clean-up and landscaping, and (3) project management, engineering and site support (See Table 4.34).

Table 4.34: Major Nuclear Decommissioning Cost Drivers.
Source: [193].

Decommissioning Cost Driver	**Share**[40]
Dismantling	25-35% of total.
Waste Treatment and Disposal	17-43% of total.
Security, Survey and Maintenance	8-13% of total.
Site Clean-up and Landscaping	5-13% of total.
Project Management, Engineering and Site Support	5-24% of total.

It is important to mention that the waste treatment and disposal share of decommissioning cost is subject to variation. Some nuclear-related economic analyses (e.g. [153, 165, 192]) include the full cost of radioactive waste disposal, including disposal of unirradiated, operational or spent fuel and decommissioning waste, within their decommissioning cost estimates [191, 192]. In contrast, other nuclear-related economic analyses only include part of the fuel-related disposal costs within their decommissioning cost estimates or do not include them at all (e.g. [191]). However, within this study, the disposal cost of unirradiated, operational or spent fuel and associated waste was treated as a component of fuel cost rather than a decommissioning cost (See Section 4.5).

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[40] Values vary more broadly from reactor to reactor.

4.6.1 Decommissioning Cost of Nuclear Power Plants and Economies of Scale

As pointed out by [191], in the nuclear sector, there are differences in decommissioning cost estimates between utilities and countries, even for similar facilities. Therefore, as acknowledged by the nuclear industry, some of the uncertainties associated with the decommissioning cost of nuclear power plants are not fully resolved until the decommissioning work is finished. However, it is well known that the decommissioning cost of nuclear power plants is not directly correlated to its capacity, especially for low rated plants. Some of the costs of the decommissioning process are nearly independent of the reactor size (e.g. plant survey, security, guarding, etc.) and, therefore, average decommissioning costs ($£/kWe$) are relatively higher for smaller plants [191].

On one hand, based on an extensive database containing the decommissioning cost of several dozens of reactors of different types, [193] claims that increasing the size of a reactor significantly decreases its average decommissioning cost ($£/kWe$). On the other hand, [191] assures that if all reactor types are considered, there is only a slight average decommissioning cost ($£/kWe$) decreasing trend with increasing capacity, mainly due to the high decommissioning costs reported for gas-cooled and small size reactors. Nonetheless, if one focuses only on water cooled reactors (>200 MWe) the correlation between reactor capacity and decommissioning cost becomes weak (weak economies of scale) and less significant (See Figure 4.15)[191].

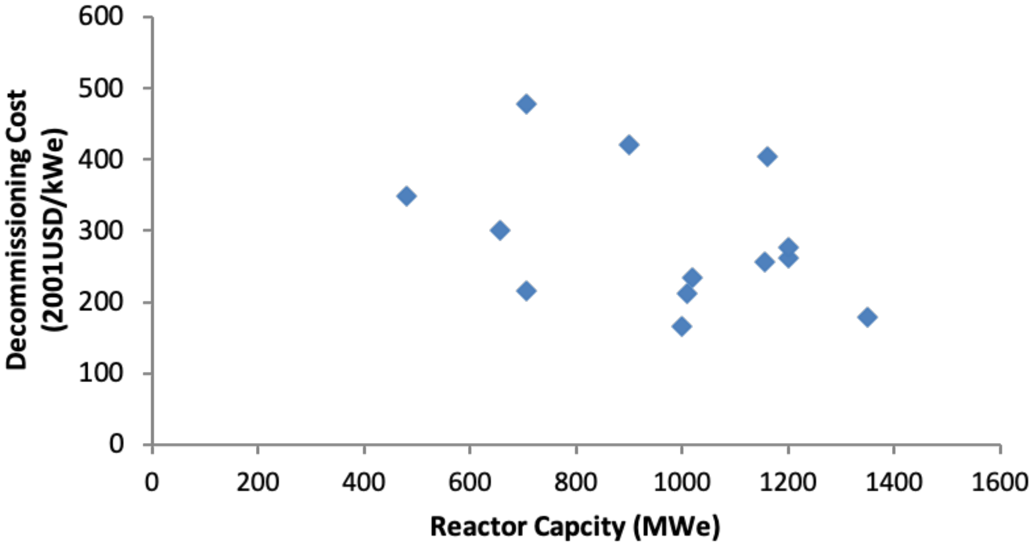

Figure 4.15: Typical Decommissioning Cost of PWRs.
Source: [191]

In fact, regarding integral PWRs in a UK context, the decommissioning cost of integral PWRs is likely to be similar to that of larger non-integral PWRs [194]. Consequently, a preliminary average decommissioning cost ($£/kWe$) estimation, is possible for SMRs assuming weak economies of scale and applying the Cost-to-Capacity method, introduced in Subsections 4.2.2.1 and 4.2.3. Then the preliminary average decommissioning cost estimation, of near term SMRs, can be improved upon application of potential correction factors (e.g. reactor type, co-siting, operating history, design improvement and availability of radioactive waste repositories), as illustrated by Equation 4.17.

$$DECOMM_1(Q_1) = DECOMM_2(Q_2)\left(\frac{Q_1}{Q_2}\right)^{n_{Decomm}-1} \times CF_1 \times CF_2 \times \ldots \times CF_N \quad (4.17)$$

Where CF_i are the correction factors that depend upon the situation assessed (e.g. 1^{st} On A Site or Nth On A Site) and:

- $DECOMM(Q)$: Average decommissioning cost (or decommissioning cost per unit capacity) of a nuclear power plant as a function of its capacity or output.
- Q: Capacity or output of the corresponding nuclear power plant.
- n_{Decomm}: Output elasticity of decommissioning cost.

4.6.2 Average Decommissioning Cost of SMRs in a UK Scenario

4.6.2.1 Application of the Cost-to-Capacity Method - Decommissioning Cost of a FOAK/NOAK SMR

In line with the methodology used to calculate the average overnight cost and the average O&M of a generic near term SMR in a UK scenario, the average decommissioning cost of a 300 MWe Integral Pressurised Water SMR was estimated assuming weak economies of scale and using Sizewell B (1198 MWe) as the reference large scale nuclear power plant. Moreover, in order to use Sizewell B for a decommissioning cost escalation, its future decommissioning cost was first investigated. In relation, by convention, it is usually assumed that the decommissioning cost of a nuclear power plant is equivalent to 15% of its overnight cost [80, 144]. However, this 15% of overnight cost estimation technique was found to be inconsistent. On one hand, this estimation method will lead to the conclusion that FOAK Nuclear Power Plant(s) (NPP) (as Sizewell B) have, or will have, a higher decommissioning cost than NOAK NPPs. On the other hand, economic analyses done by the UK's Department of Energy and

Climate Change (DECC), now known as Department for Business, Energy & Industrial Strategy (DBEIS), show no variation between the decommissioning cost of FOAK NPPs and NOAK NPPs [153, 165]. Therefore, the OECD [191] central decommissioning cost estimate (345 $£/kWe^{41}$) was assumed to be the future decommissioning cost of Sizewell B. Lastly, the preliminary decommissioning cost of near term SMRs was calculated upon application of the Cost-to-Capacity method, assuming weak economies of scale ($n_{Decomm} = 0.7 - 0.9$), 5-10% discount rates and that the decommissioning cost was evenly distributed among the typical 60 years operational life predicted for SMRs. The results obtained are now presented in Table 4.35.

Table 4.35: Preliminary Average Decommissioning Cost of a FOAK/NOAK 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK/NOAK Large Reactor vs. FOAK/NOAK-First On A Site SMR Average Decommissioning Cost ($£/kWe$) - Preliminary Estimation						
Output Elasticity of Decommissioning Cost (n_{Decomm})	0.7	0.8	0.9	0.7	0.8	0.9
Undiscounted Decommissioning Cost of Reference Plant (2017 GBP/kWe)	345					
Cost-to-Capacity Factor	×1.51	×1.32	×1.15	× 1.51	×1.32	×1.15
Undiscounted Decommissioning Cost SMR (2017 GBP/kWe)	523	456	397	523	456	397
Discount rate (%)	5			10		
Discounted Decommissioning Cost SMR (2017 GBP/kWe)	173	151	131	96	83	73

4.6.2.2 Correction Factors

As noted by [145], there could be 7 differential decommissioning cost factors (including economies of scale) between SMRs and large reactors. In other words, the preliminary decommissioning cost estimation, presented in the previous subsection, has to be refined given that the Cost-to-Capacity method assumes that SMR and large reactors are equal except for size. Nevertheless, except for economies of scale, some of the potential differential cost factors between SMRs and large reactors may not lead to significant cost reductions or may be highly speculative. Consequently, the applicability of these potential correction factors was analysed and the conclusions are presented below.

Reactor Type

Different reactor types could lead to different decommissioning costs due to physical/geometrical differences [145]. For example, the decommissioning of non-PWRs is likely to be more challenging than the decommissioning of PWRs, due to larger

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[41] Figure originally presented in 2001 USD, adjusted for inflation to 2017 USD using [186] and converted to British Pound Sterling using 1 $GBP = 1.282692$ USD [187].

quantities of irradiated materials, which are less familiar to the nuclear industry (e.g. irradiated lead, sodium or salt, etc.). Moreover, [191] found that in the case of water reactors, the average decommissioning cost ($£/kWe$) seems to be independent of the reactor type. In other words, regardless of the specific type of water reactor, the amount of work required to decommission a water reactor is common to all large metal and concrete nuclear facilities. Additionally, according to [194], decommissioning of Integral Small PWRs will not present fundamentally different challenges from those of decommissioning of conventional large scale PWRs. Consequently, no decommissioning cost saving, or penalty, due to reactor type is likely to be applicable to near term SMRs.

Co-siting

Having multiple units at a single site takes full advantage of learning economies due to the experience acquired from decommissioning of the first unit(s). Nth On A Site units have the advantage of reused, refined or optimised tools and techniques. Therefore, decommissioning schedules might be accelerated reducing management costs, for Nth on Site NPPs [195]. Similarly, the more units you have on a site, the more infrastructure facilities are shared and, therefore, the more site operating costs are reduced (on a per reactor basis) [191]. In consequence, [193] suggests a 22% decommissioning cost reduction for Nth On A Site SMRs. Nevertheless, this cost reduction is likely to overestimate the impact of co-siting, just as [193] might have overestimated the strength of economies of scale, given that the cost reduction was estimated based on a regression analysis performed with dozens of reactors of different types, not just typical water reactors. At the same time, [145] suggests that the decommissioning cost reduction due to co-siting is equivalent to the overnight cost reduction due to co-siting. Therefore, recalling Subsection 4.2.4.3, a conservative 15% decommissioning cost reduction for SMRs, as a result of co-siting economies, seems realistic.

Operating History

Incidents such as fuel damage, contamination spread, fuel leakage or water chemistry events, result in a more complex decommissioning process and, as a result, more expensive [145, 191]. In relation, due to its passive safety features, SMRs could reduce the risk of occurrence of the incidents previously mentioned. Nevertheless, these incidents are very infrequent and, therefore, a decommissioning cost reduction for SMRs due to a different or safer operating history would be highly speculative [193]. In other words, within this study, no decommissioning cost reduction resulting from a potentially safer operating history was granted to SMRs.

Modular and Integral Design

Decommissioning of full factory assembled reactors could be technically easier than that of large reactors given that they could be transported back to the factory in an assembled form. Later on, assuming an optimised supply chain, dismantling and recycling of components is expected to be cheaper at a centralised factory, compared to on-site decommissioning [144]. In contrast, due to the small size of SMRs, there could be challenges with accessibility for decontamination and dismantling [163]. Nonetheless, in the view of [194], decontamination and dismantling of Integral Pressurised Water SMRs is considered credible, considering the existing tooling within the UK civil nuclear industry. Similarly, passive safety features could reduce the amount of waste produced by Integral SMRs. Consequently, [193] estimated that the modular and integral design of near term SMRs could reduce the decommissioning cost by 13-19%, compared to large reactors.

Availability of Radioactive Waste Repositories

The extent and, therefore, the cost of dismantling and packaging required for the radioactive waste produced during decommissioning of nuclear power plants is, in a way, determined by the size of the end repository. In contrast with small repositories, large repositories could be able to accommodate whole reactor vessels. Therefore, in comparison with large reactors, more suitable repositories might be available for SMRs, due to smaller dimensions and components [145]. Nonetheless, economic analyses assume the availability of suitable radioactive waste repositories, regardless of the type of reactors [193]. This is, probably, due to the fact that owners/operators can always choose a deferred decommissioning strategy to ensure the availability of a suitable repository [191]. At the same time, not only the decommissioning schedule (immediate or deferred) is not likely to have a significant impact on the overnight decommissioning cost, but also the materials from the core and primary circuits of near term SMRs are not unknown to the UK's nuclear decommissioning industry [191, 194]. As a result, the availability of radioactive waste repositories has not been considered, in this study, as a differential factor between the decommissioning cost of SMRs and large reactors.

4.6.2.3 SMRs' Adjusted Average Decommissioning Cost

Considering applicable correction factors (See Table 4.36), the average decommissioning cost of a 300 MWe Integral Pressurised Water SMR was estimated, applying Equation 4.17, for two different scenarios: (1) FOAK/NOAK First On A Site SMR (See Table 4.37), and (2) FOAK/NOAK Nth On A Site SMR (See Table 4.38). Similarly, low ($n_{Decomm} = 0.9$), central ($n_{Decomm} = 0.8$), and high ($n_{Decomm} = 0.7$) estimates are provided, for each scenario. Furthermore, discounted values were calculated as well, for 5-10% discount rates and assuming that the decommissioning cost was evenly distributed among a 60 years operational lifetime.

Table 4.36: Assumptions made for the application of an adjusted Cost-to-Capacity Generic Method.
Decommissioning Cost.

Cost-to-Capacity Method Corrections	**Assumed Average Decommissioning Cost Reduction**	**Correction Factor**
Modular and Integral Design	16%	× .84
Co-Siting	15%	× .85

Table 4.37: Adjusted Average Decommissioning Cost of a FOAK/NOAK & First On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK/NOAK Large Reactor vs. FOAK/NOAK-First On A Site SMR Average Decommissioning Cost (£/kWe) - Refined Estimation						
Output Elasticity of Decommissioning Cost (n_{Decomm})	0.7	0.8	0.9	0.7	0.8	0.9
Undiscounted Decommissioning Cost of Reference Plant (2017 GBP/kWe)	345					
Cost-to-Capacity Factor	×1.51	×1.32	×1.15	× 1.51	×1.32	×1.15
Modular and Integral Design	×0.84					
Cumulative Correction Factor	×1.27	×1.11	×0.96	×1.27	×1.11	×0.96
Undiscounted Decommissioning Cost SMR (2017 GBP/kWe)	440	383	333	440	383	333
Discount rate (%)	5			10		
Discounted Decommissioning Cost SMR (2017 GBP/kWe)	146	127	110	80	70	61

Table 4.38: Adjusted Average Decommissioning Cost of a FOAK/NOAK & Nth On A Site 300 MWe Integral Pressurised Water Small Modular Reactor.

FOAK/NOAK Large Reactor vs. FOAK/NOAK-Nth On A Site SMR Average Decommissioning Cost (£/kWe) - Refined Estimation						
Output Elasticity of Decommissioning Cost (n_{Decomm})	0.7	0.8	0.9	0.7	0.8	0.9
Undiscounted Decommissioning Cost of Reference Plant (2017 GBP/kWe)	345					
Cost-to-Capacity Factor	×1.51	×1.32	×1.15	× 1.51	×1.32	×1.15
Modular and Integral Design	×0.84					
Co-siting	×0.85					
Cumulative Correction Factor	×1.08	×0.94	×0.82	×1.08	×0.94	×0.82
Undiscounted Decommissioning Cost SMR (2017 GBP/kWe)	374	325	283	374	325	283
Discount rate (%)	5			10		
Discounted Decommissioning Cost SMR (2017 GBP/kWe)	124	108	94	68	59	52

From Tables 4.37 and 4.38, depending on the scenario assessed and the extent of economies of scale, the average decommissioning cost of a 300 MWe Integral Pressurised Water SMR could be anywhere between 18% lower and 27% higher than that of equivalent large reactors. Nevertheless, focusing only on the central estimates, a more realistic -6% to +11% is obtained (See Figure 4.16). In other words, near term SMRs could have similar, or even lower, decommissioning costs than large scale PWRs.

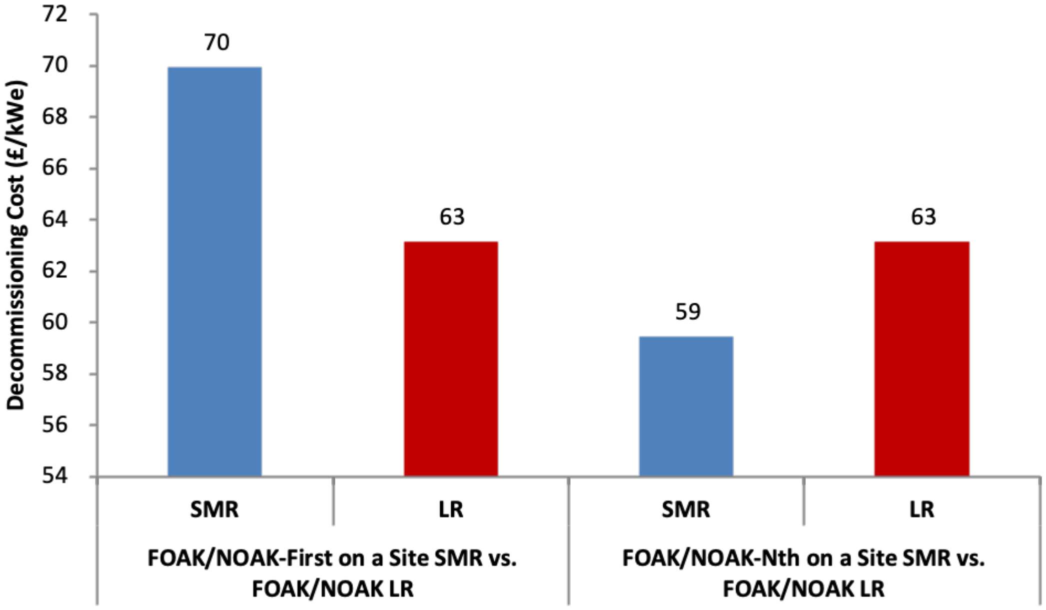

Figure 4.16: Central ($n_{Decomm} = 0.8$) Discounted Decommissioning Cost Estimates of FOAK/NOAK SMRs and Typical FOAK/NOAK Large Scale Nuclear, a 10% discount rate.
Source for Large Scale Nuclear: [191]

4.6.3 Test Case - Multiple (4) SMRs vs. Single LR - Decommissioning Cost

In line with the scenarios presented in previous sections, the test case of 4 SMRs vs. 1 LR is now presented for central decommissioning estimates, considering the following scenarios (See Table 4.39) and assumptions:

Table 4.39: Scenarios Considered for the 4 SMRs vs. 1 LR Test Case - Decommissioning Cost.

Scenario A
1 FOAK + 3 NOAK-Nth On A Site SMRs vs. 1 FOAK LR
Scenario B
1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs vs. 1 NOAK-1st On A Site LR

- **Output Elasticity of Decommissioning Cost:** $n_{Decomm} = 0.8$.
- **Central Undiscounted Decommissioning Cost SMRs (See Tables 4.37-4.38):**
  FOAK/NOAK-1st On A Site = 383 $£/kWe$.
  FOAK/NOAK-Nth On A Site = 325 $£/kWe$.
- **Central Undiscounted Decommissioning Cost Estimates of Large Reactors (From [191]):**
  FOAK/NOAK = 345 $£/kWe$[42].
- **Discount Rate:** 10%.
- **Construction Period:**
  FOAK SMRs = 4 years.
  NOAK SMRs = 3 years.
  FOAK Large Reactor = 8 years.
  NOAK Large Reactor = 6 years.
- **Start of Operation:** The start of operation date of the large reactor and of the first SMR are assumed to coincide.
- **Construction Schedule SMRs:** The first construction year of a subsequent SMR is assumed to match the second construction year of a previous SMR.

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[42] Figure originally presented in 2001 USD, adjusted for inflation to 2017 USD using [186] and converted to British Pound Sterling using 1 $GBP = 1.282692\ USD$ [187].

- **Operational Lifetime:**

  SMRs = 60 years.

  Large Reactor = 60 years.

- **Decommissioning Scheme:** Immediate.

In contrast with O&M (See Subsection 4.4.2.3) and fuel costs (See Subsection 4.5.1), it was found that multiple SMRs will, almost certainly, have slightly lower decommissioning costs than a single equivalent large reactor. On one hand, Scenario A indicates that 4 SMRs (1 FOAK + 3 NOAK-Nth On A Site) could have an average decommissioning cost 8% lower than FOAK LRs. On the other hand, Scenario B suggests that 4 SMRs (1 NOAK-1st On A Site + 3 NOAK-Nth On A Site) could have an average decommissioning cost 14% lower than NOAK LRs. In relation, considering a scenario that resembles the scenarios here studied, [193] estimated that 4 SMRs could have a decommissioning cost 4% lower than a single large reactor. Consequently, the results here presented are similar to previous estimations.

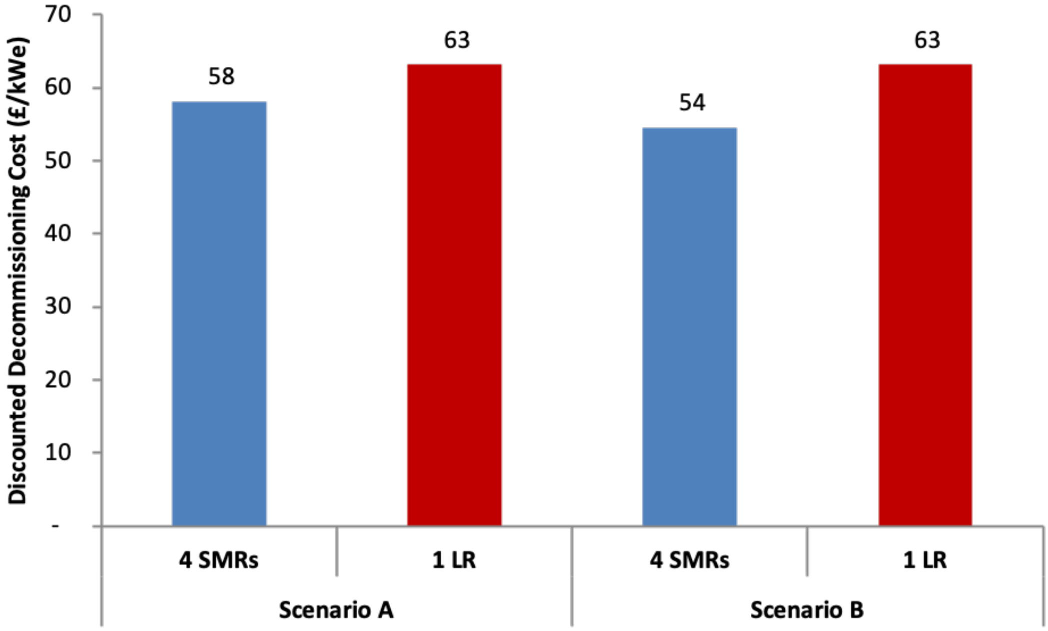

Figure 4.17: Test Case: 4 SMRs vs. 1 LR - Discounted Decommissioning Cost. Scenario A - 1 FOAK + 3 NOAK-Nth On A Site SMRs vs. 1 FOAK LR. Scenario B - 1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs vs. 1 NOAK-1st On A Site LR.

Finally, considering Tables 4.37-4.38 and Figure 4.17, on a one to one basis, SMRs and large reactors are likely to have similar average decommissioning costs. However, multiple SMRs have strong chances of achieving a marginally lower average decommissioning cost than a single equivalent large reactor.

4.7 Cash Inflow

On one hand, the cash outflow of SMRs will be determined by their overnight cost and size of investment, operation and maintenance cost, fuel cost and decommissioning cost. On the other hand, the cash inflow of SMRs will depend upon their electrical capacity, their capacity factor and the wholesale price of electricity (See Equation 4.18). In relation, as detailed in Section 4.1, for this study a generic 300 MWe Integral Pressurised Water SMR was selected as a representative near term SMR. Furthermore, as it was previously mentioned in Subsection 4.4.2.2 and later discussed in Subsection 5.2.2.1, SMRs might display capacity factors within the 90-95% range. Consequently, for this study, a conservative 90% capacity factor has been assumed due to the fact that high capacity factors are only achievable through operational learning and, as a result, time [168]. Finally, the annual cash inflows of SMRs will be directly proportional to the corresponding wholesale price of electricity. Unfortunately, long term projections of the wholesale price of electricity are highly speculative and scarce.

$$Discounted\ Cash\ Inflow = \sum_{t=t_{start}}^{t_{end}} \frac{P_t \times 8760 \times Cf_t}{(1+r)^{t-t_0}} \times R_t \tag{4.18}$$

Where:

- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- t_0: A point in time (a particular year) to which all cash inflows are discounted. Typically assumed to coincide with the start of operations.
- P_t: Electrical capacity of the power plant under consideration, at year t (MWe). To simplify calculations, it is normally assumed to remain constant throughout the plant's lifetime.
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100). To simplify calculations, it is normally assumed to remain constant throughout the plant's lifetime.
- 8760: Total number of hours in a year (h).
- R_t: Reference selling price of electricity in year t (£/MWh).
- r: Reference discount rate, for the period of interest (%/100).

4.7.1 Wholesale Price of Electricity

In the wholesale electricity market, energy suppliers buy energy from energy generators at wholesale prices which are normally determined by supply and demand. Later on, energy suppliers sell electricity to their customers at a higher price. Moreover, in general, wholesale electricity market prices oscillate between 40-50 $£/MWh$ [196]. However, the previous wholesale price range could not be true beyond the short and medium term. In the long term, a number of factors could influence the UK's wholesale electricity market behaviour: (1) Whether gas-fired generation will continue to be a key price driver, (2) potential improved interconnector flexibility, (3) contribution of small scale renewables, (4) usage of electric vehicles, and (5) new infrastructure (e.g. offshore wind and a new fleet of large scale nuclear) [197]. However, the calculation of long run wholesale electricity market prices is not the objective of this study and, consequently, for cash inflow calculations it has been assumed that, in the future, this market will display the same trends it showed during the years 2007-2018 (See Figure 4.18). In other words, analysing the evolution of the ICIS Power Index [198] during the period 2007-2018, low (28.76 $£/MWh$, two standard deviations), central (48.77 $£/MWh$, average) and high (66.80 $£/MWh$, two standard deviations) long run wholesale electricity price scenarios were identified.

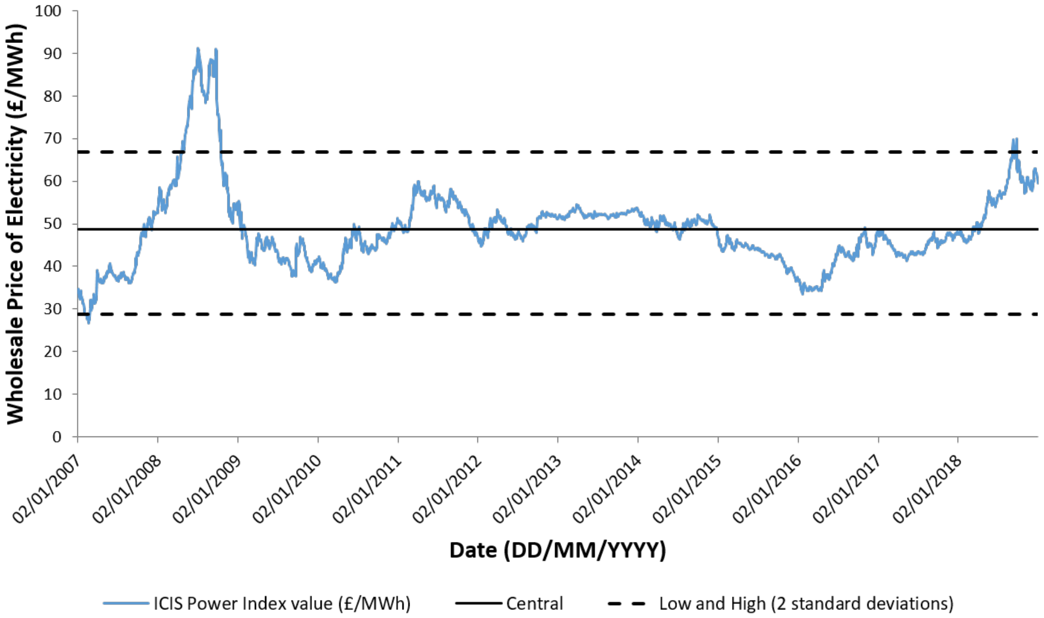

Figure 4.18: Derivation of Long Term Low, Central and High Wholesale Electricity Price Scenarios, based on UK's Wholesale Electricity Prices during the period 2007-2018.
Data Source: [198]

In addition, apart from the three previously mentioned scenarios, for cash inflow calculations two more scenarios were identified as necessary in order to account for market interventions. On one hand, the UK Government agreed a strike price of approximately 104.39 £/MWh, in 2017 prices[43], with NNB Generation Company Limited, which will operate Hinkley Point C, for the first 35 years [199]. On the other hand, the UK Government guaranteed a strike price of about 89.39 £/MWh, in 2017 prices, for the Wylfa Newydd project in Anglesey [200]. Although the Wylfa Newydd project was abandoned in 2020 after Hitachi failed to reach a funding agreement with the UK Government [201], it has been assumed that the strike price awarded to Hinkley Point C is unlikely to be repeated. Therefore, the 89.39 £/MWh originally agreed for the Wylfa Newydd project was included in this study as it is more likely to resemble future strike prices awarded to nuclear than the 104.39 £/MWh of Hinkley Point C. In comparison, in September 2019 the UK Government awarded 2.6 GWe of offshore wind capacity at 44.90 £/MWh, in 2017 prices[43], for delivery in 2023/24 [202].

4.7.2 Cash Inflow of SMRs in a UK Scenario

In order to illustrate the potential cash inflow of near term SMRs in a UK scenario, the discounted cash inflow of a representative 300 MWe Integral Pressurised Water SMR was calculated for the five wholesale prices of electricity scenarios, detailed in the previous Subsection, assuming an operational lifetime of 60 years, constant wholesale electricity prices, constant electrical capacity (300 MWe), constant capacity factor (90%) and 5-10% discount rates. Results are presented below in Table 4.40.

Table 4.40: Lifetime Cash inflow of a 300MWe Integral Pressurised Water SMR. Figures quoted in 2017 prices.

Wholesale Price of Electricity (£/MWh)	**Undiscounted Value (£)**	**5% Discount Rate (£)**	**10% Discount Rate (£)**
28.76	4,081,077,487	1,351,908,203	745,740,256
48.77	6,920,374,661	2,292,461,073	1,264,568,485
66.80	9,480,033,233	3,140,380,141	1,732,298,011
89.39	12,685,513,680	4,202,235,822	2,318,039,354
104.39	14,814,193,680	4,907,387,822	2,707,015,642

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[43] Figure originally presented in 2012 prices. Converted to 2017 prices upon utilisation of the Bank of England Inflation Calculator [152].

4.8 Chapter Summary

Economic Characterisation of Small Modular Reactors in a UK Scenario

- **Unique Contribution:** The cost breakdown, on a per unit capacity basis, of near term SMRs in a UK context was estimated upon utilisation of a refined Cost-to-Capacity method when applicable (See Table 4.41). Otherwise, the corresponding cost components were calculated from first principles. In any case, low, central and high cost scenarios were studied.
    - The characteristics of a representative near term SMR were recognised by investigating the most promising SMR designs and previous SMR feasibility studies. As a result, a 300 MWe integral pressurised water SMR was identified as a representative SMR which would also be a good candidate for cost estimations based on cost-capacity estimation techniques.
    - The extent to which economies of scale influence PWR technologies was analysed independently for every cost component. Consequently, realistic output elasticities were identified for capital, O&M and decommissioning costs. Later on, cost estimations were done using the Cost-to-Capacity model with Sizewell B as the reference plant. Finally, these cost estimations were refined upon application of relevant and demonstrated correction factors.
    - In contrast, acknowledging that fuel costs derived assuming economies of scale would be highly inaccurate, the fuel cost of near term SMRs was calculated from first principles considering the potential reactor core specifications of a 300 MWe integral pressurised water SMR.

Table 4.41: Summary of the Refined Cost-to-Capacity Method Followed to Estimate the Central Generation Costs of Near Term NOAK SMRs.

Cost Component	**Extent of Economies of Scale**	**Central Output Elasticity (n)**	**Correction Factors**
Capital	Medium	0.6	• Design Improvement. • Modular Construction. • Construction in Series. • Co-siting (If applicable).
O&M	Medium	0.65	• Operational Learning. • Co-siting (If applicable).
Fuel	Null	1	Not Applicable.
Decommissioning	Weak	0.8	• Modular and Integral Design. • Co-siting (If applicable).

- **Unique Contribution:** Having estimated the cost break down of near term single SMRs in a UK context, the results were utilised to extend our current level of understanding of multiple SMR economics (See Table 4.42). Previous studies of multiple SMR economics were limited to the capital cost component and were not made assuming country specific conditions.

Table 4.42: Central Average Cost Estimates of Single and Multiple (4) NOAK SMRs Relative to the Average Costs of Typical NOAK Large Scale PWRs.

Generating Cost	**Single SMRs Relative to LR**	**Multiple (4) SMRs Relative to LR**
Capital Cost (£/MWe)	+16% to +25%	-10% to +4%
O&M Cost (£/MWe)	+75%	+36% to +45%
Fuel Cost (£/MWe)	+61% to +82%	+51% to +59%
Decommissioning Cost (£/MWe)	+11%	-14% to -8%
Total Cost (£/MWe)	+30% to +43%	+2% to +20%

- **Unique Contribution:** Results suggest that single SMRs have little chances to be as cost-efficient as large scale PWRs unless a significant overnight cost reduction due to construction in a factory environment is demonstrated. In contrast, multiple (4) SMRs are likely to take advantage of co-siting economies and the time value of money to achieve cost-efficiencies comparable to those of large scale PWRs (See Figures 4.19-4.20).

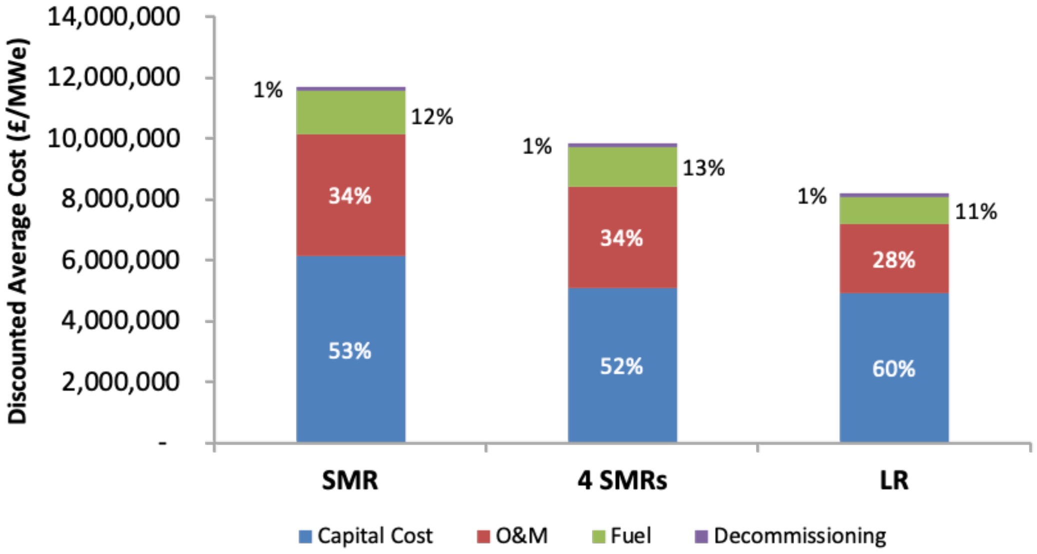

Figure 4.19: Central Estimates - Discounted Total Average Cost of Single NOAK SMRs, Multiple NOAK SMRs and Typical Large PWRs, Considering 5% Interest Rates, 5% Discount Rates, an Open Fuel Cycle and a 3-batch Refuelling Scheme.

- **Unique Contribution:** Results indicate that, if no further cost reductions are demonstrated, the only scenarios in which single SMRs could be an attractive electricity generation technology, in terms of cost-efficiency, would be one in which the size of investment in absolute terms (£) was a limitation or a scenario where no other technology was suitable for the location of interest (e.g. remote locations).

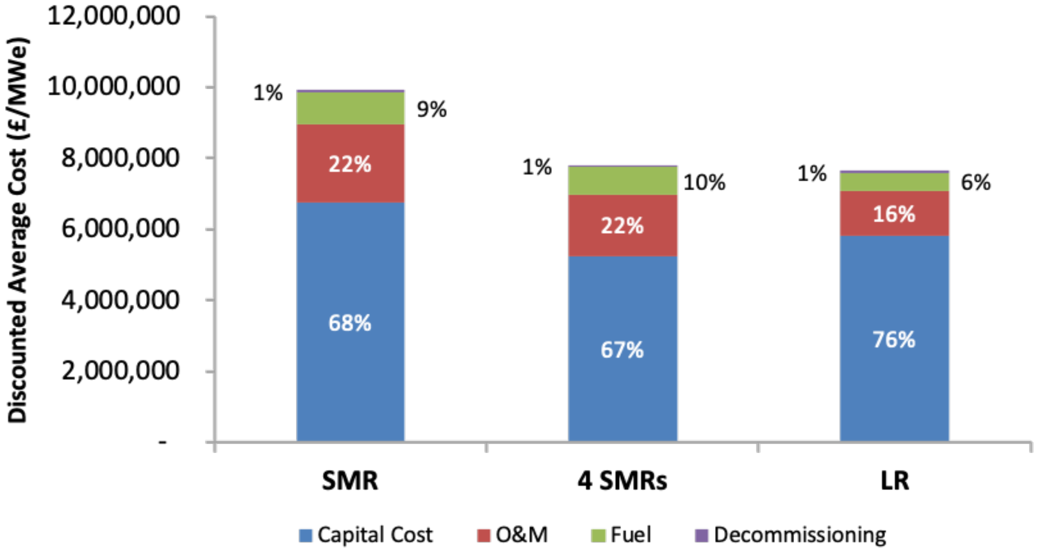

Figure 4.20: Central Estimates - Discounted Total Average Cost of Single NOAK SMRs, Multiple NOAK SMRs and Typical Large PWRs, Considering 10% Interest Rates, 10% Discount Rates, an Open Fuel Cycle and a 3-batch Refuelling Scheme.

- **Unique Contribution:** A 3-batch refuelling scheme with 24 months refuelling intervals was found to be more cost efficient for near term SMRs than a single batch refuelling scheme with 48 months refuelling intervals.

Chapter 5

ATTRACTIVENESS OF INVESTMENT AND ECONOMIC SUSTAINABILITY OF SMALL MODULAR NUCLEAR REACTORS IN A UK SCENARIO

5.1 Attractiveness of Investment

5.1.1 Financial Figures of Merit

5.1.1.1 Size of Investment

As previously discussed in Section 4.3, depending on the scenario and interest rate considered, the average size of investment (£/kWe) of near term SMRs has been estimated, by the author of this study, to be anywhere between 5% lower and 50% higher than the average size of investment (£/kWe) of equivalent large scale PWRs. Nonetheless, due to the similarities between the low and central scenarios presented below in Figures 5.1-5.2 and NNL calculations (See [17]), it has been assumed that the low and central scenarios are the scenarios most likely to resemble the size of investment of near term SMRs in a UK context. Consequently, while the size of investment in absolute terms (£) of near term SMRs will certainly be smaller than that of large scale PWRs due to their reduced capacity, their cost-efficiency ($£/kWe$) could only be comparable to that of large reactors in the best case scenario. In other words, assuming equal conditions, the size of investment (£) of NOAK SMRs might be in the order of billions while typical NOAK large scale PWRs tend to have sizes of investment (£) in the order of tens of billions. However, results suggest that single SMRs are likely to be up to 30% more expensive per unit capacity than large scale PWRs.

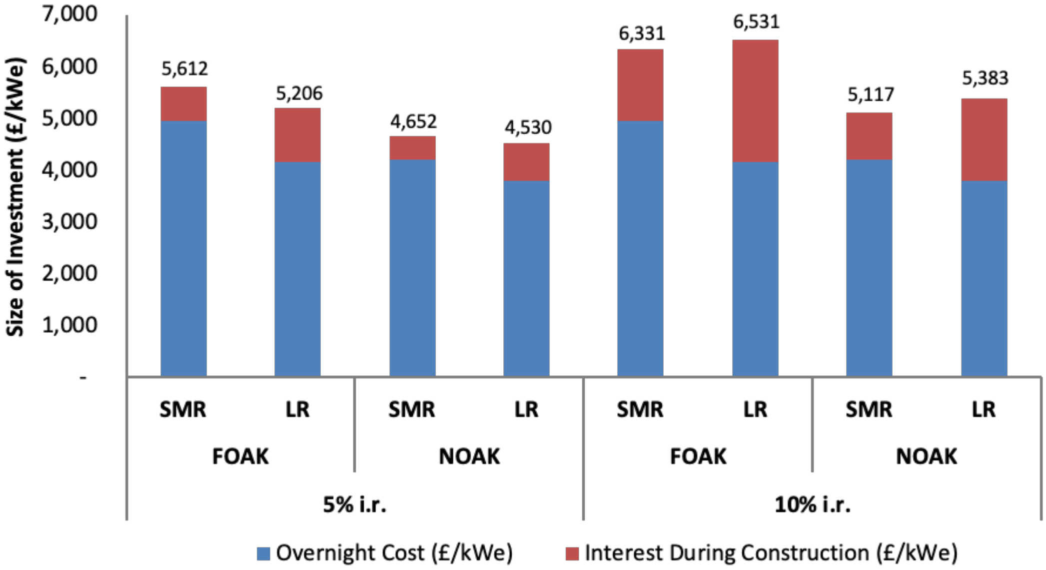

Figure 5.1: Size of Investment - Low estimates - of near term SMRs and typical large scale PWRs, considering 5-10% interest rates.

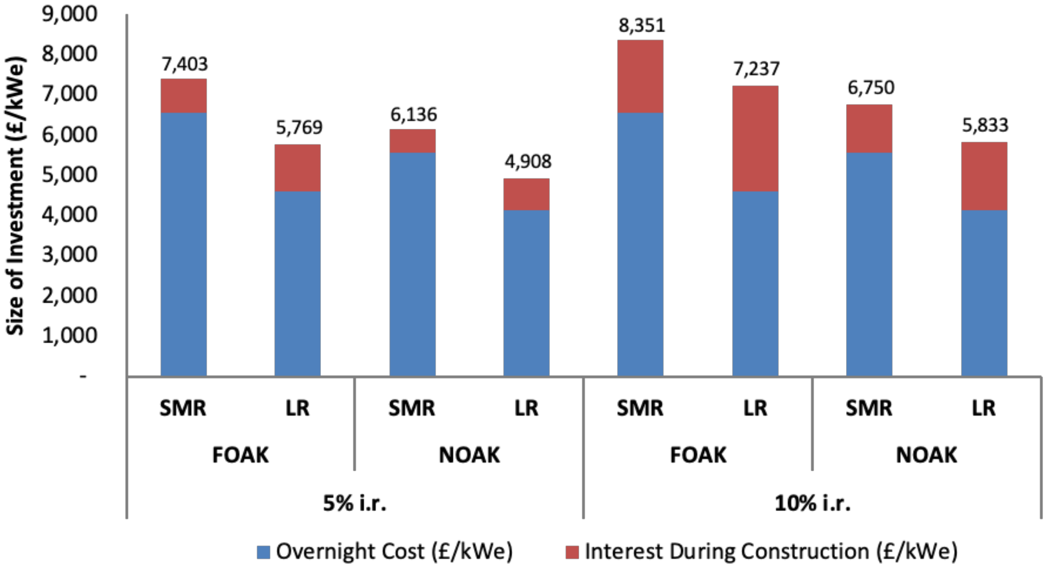

Figure 5.2: Size of Investment - Central estimates - of near term SMRs and typical large scale PWRs, considering 5-10% interest rates.

5.1.1.2 Net Present Value (NPV)

Considering the potential cash flows of a generic 300 MWe Integral Pressurised Water SMR, previously shown in Sections 4.3-4.7, Discounted Cash Flow (DCF) analyses were made considering 5-10% interest and discount rates and following Equation A.2 in Appendix A.2. Furthermore, following these Discounted Cash Flow (DCF) analyses, three scenarios were created as follows:

- Low NPV: high capital cost, high O&M cost, high fuel cycle cost, high decommissioning cost and high wholesale price of electricity or wholesale electricity market intervention.
- Central NPV: central capital cost, central O&M cost, central fuel cycle cost, central decommissioning cost and central wholesale price of electricity or wholesale electricity market intervention.
- High NPV: low capital cost, low O&M cost, low fuel cycle cost, low decommissioning cost and low wholesale price of electricity or wholesale electricity market intervention.

Similarly, as indicated in Subsection 4.7.1, five different constant wholesale prices of electricity were considered (low, central, high, Hinkley Point C's strike price and Wylfa Newydd's strike price), in order to reflect UK specific wholesale electricity market conditions and wholesale electricity market interventions. Lastly, the NPV of near term SMRs was estimated for FOAK, NOAK-First On A Site and NOAK-Nth On A Site SMRs, working on an open fuel cycle and on a 1-batch or 3-batch refuelling scheme. Results are now presented below in Figures 5.3 - 5.5.

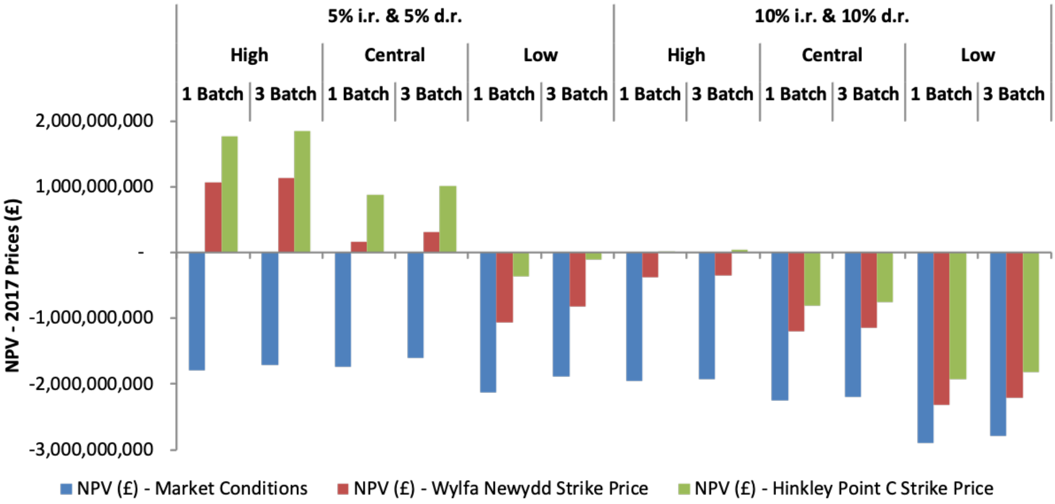

Figure 5.3: Net Present Value estimates of FOAK SMRs working on an open fuel cycle basis and 1-3 batch refuelling schemes, considering 5-10% interest and discount rates.

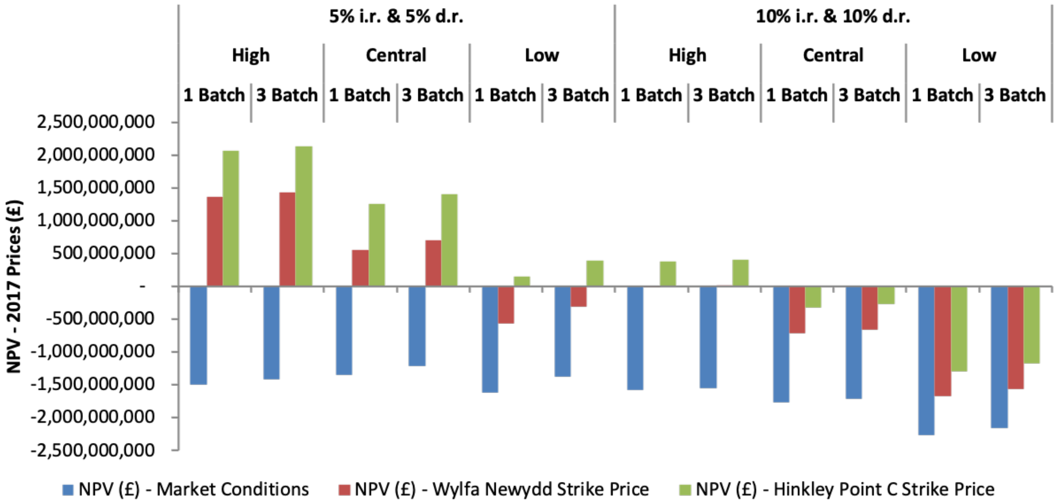

Figure 5.4: Net Present Value estimates of NOAK-1st On A Site SMRs working on an open fuel cycle basis and 1-3 batch refuelling schemes, considering 5-10% interest and discount rates.

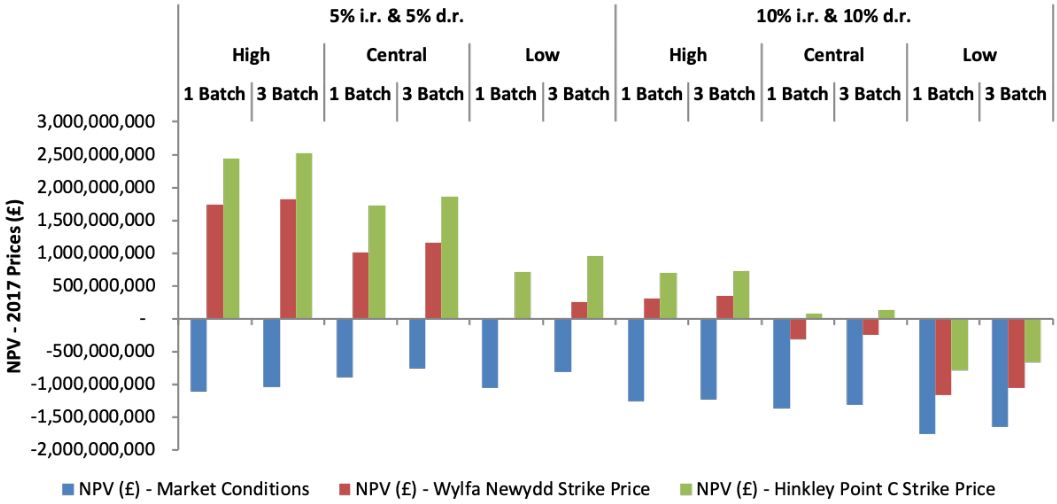

Figure 5.5: Net Present Value estimates of NOAK-Nth On A Site SMRs working on an open fuel cycle basis and 1-3 batch refuelling schemes, considering 5-10% interest and discount rates.

From Figures 5.3 - 5.5, near term SMRs, are unlikely to be profitable unless there is a market intervention or government incentive/collaboration. As pointed out in Subsection 4.7.1, statistically speaking, the wholesale price of electricity is likely to be within the 28.76-66.80 $£/MWh$ range, based on UK specific historical data. Nonetheless, considering 5-10% interest and discount rates, for SMRs to achieve the break-even point the suppliers would have to sell electricity at prices within the following ranges, depending on the scenario:

- FOAK SMRs: 68.51-175.23 £/MWh.
- NOAK-1st On A Site SMRs: 62.27-150.66 £/MWh.
- NOAK-Nth On A Site SMRs: 54.13-130.96 £/MWh.

Not only prices of electricity higher than those of the wholesale electricity market seem to be necessary if a positive NPV is desired, but also a low interest/discount rate. Similarly, secondary findings indicate that, economically speaking, a 3-batch refuelling scheme might be more attractive than a single batch refuelling scheme. Lastly, as previously mentioned in Subsection 4.2.4.3 and Section 4.8, near term SMRs might achieve better financial performances than those shown above if a significant overnight cost reduction due to construction in a factory environment is demonstrated. Therefore, the potential financial benefits of this 'factory-built factor' are later investigated in Subsection 5.3.1.

5.1.1.3 Internal Rate of Return (IRR)

As first mentioned in Subsection 3.2.1.3, the IRR is the discount rate which makes the NPV = 0. In relation, the IRR rule is to accept an investment project if the opportunity cost of capital (aka weighted average cost of capital or discount rate) of the corresponding firm is less than the IRR. Similarly, the higher the IRR the more attractive an investment project becomes [69]. Furthermore, in practical terms, the calculation of the IRR usually involves trial and error and the simplest way to calculate it is to plot the NPV as a function of cost of capital (or discount rate) and look for the zeros of the function [203]. Consequently, considering the central cash flow estimates of a generic 300 MWe Integral Pressurised Water SMR, presented in Sections 4.3-4.7, the NPV of FOAK and NOAK Integral Pressurised Water SMRs was plotted as a function of discount rate, for 0-10% interest rates (i.r.) and assuming a 3-batch refuelling scheme due to its resemblance with the refuelling schemes of current nuclear energy technologies. Similarly, the impact of market interventions was also investigated by replacing the central wholesale electricity price estimate of the British market (48.77 £/MWh) with the Wylfa Newydd strike price (89.39 £/MWh) and the Hinkley Point C strike price (104.39 £/MWh). Finally, from Figures 5.6 - 5.8, the zeros of the corresponding NPV functions were identified by inspection and, therefore, the IRRs were found. As a result, the IRRs of near term SMRs are presented below in Tables 5.1 - 5.3.

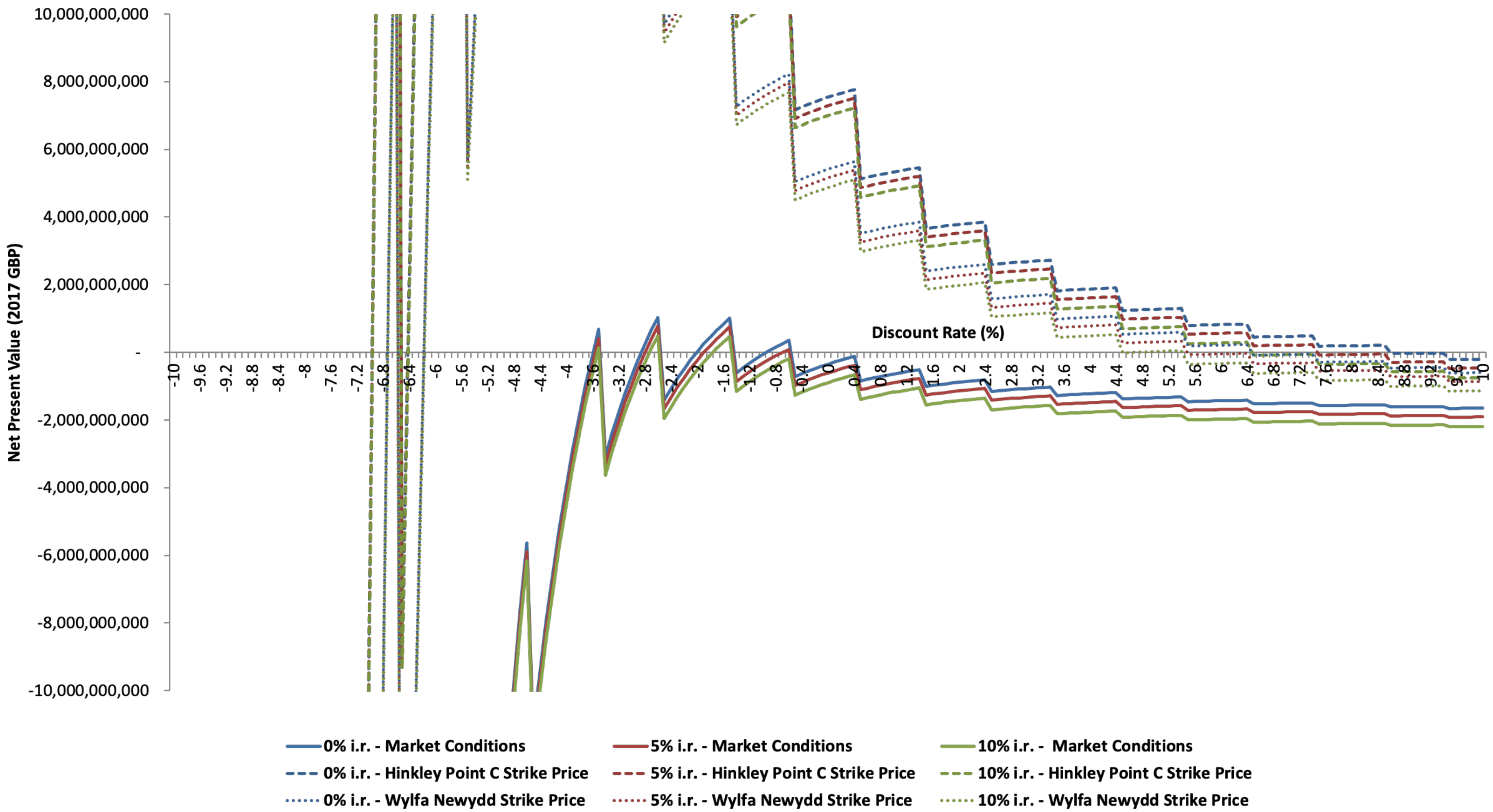

Figure 5.6: NPV estimates, as a function of discount rate, of FOAK SMRs working on an open fuel cycle basis and a 3 batch refuelling scheme, considering 0-10% interest rates.

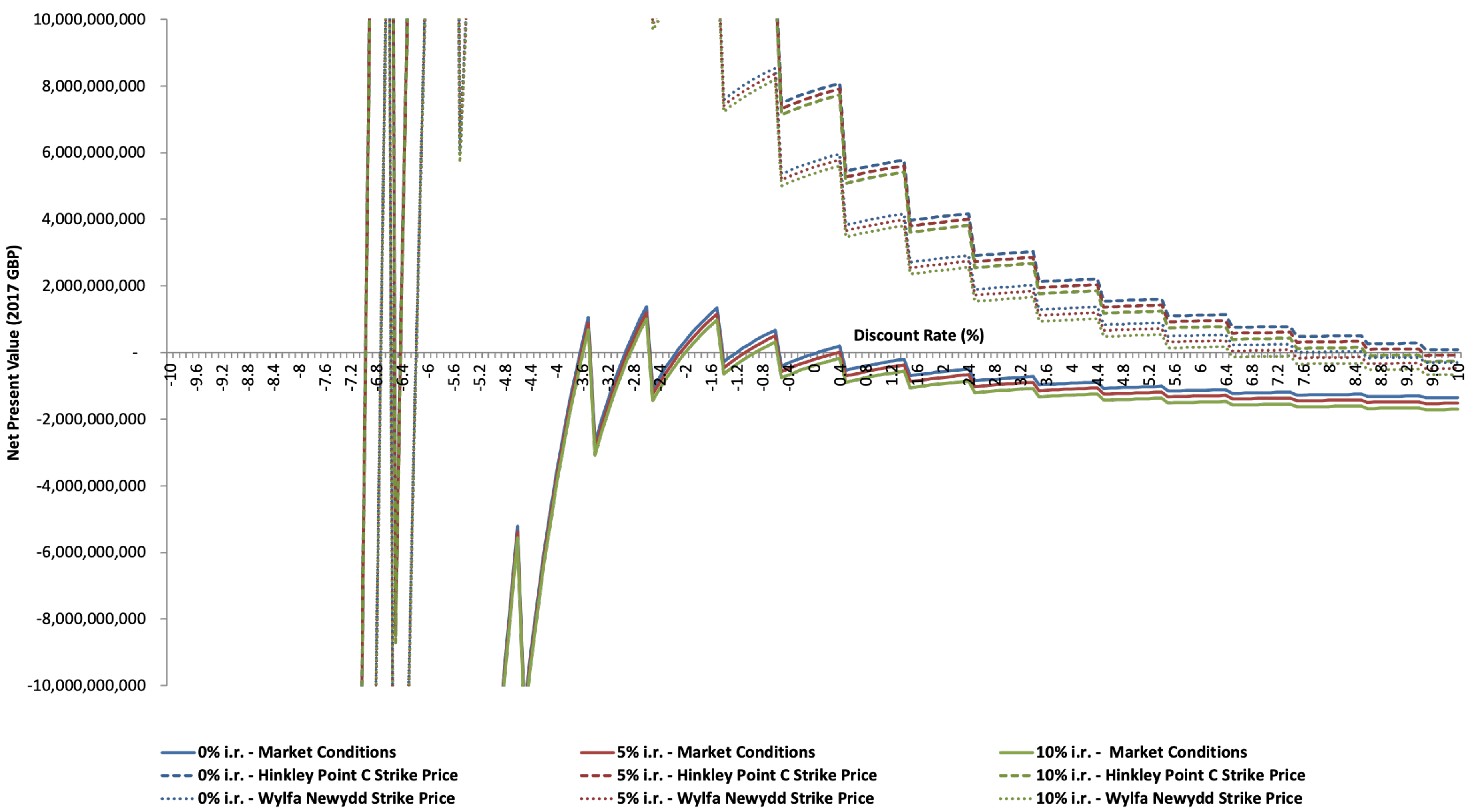

Figure 5.7: NPV estimates, as a function of discount rate, of NOAK & 1st On A Site SMRs working on an open fuel cycle basis and a 3 batch refuelling scheme, considering 0-10% interest rates.

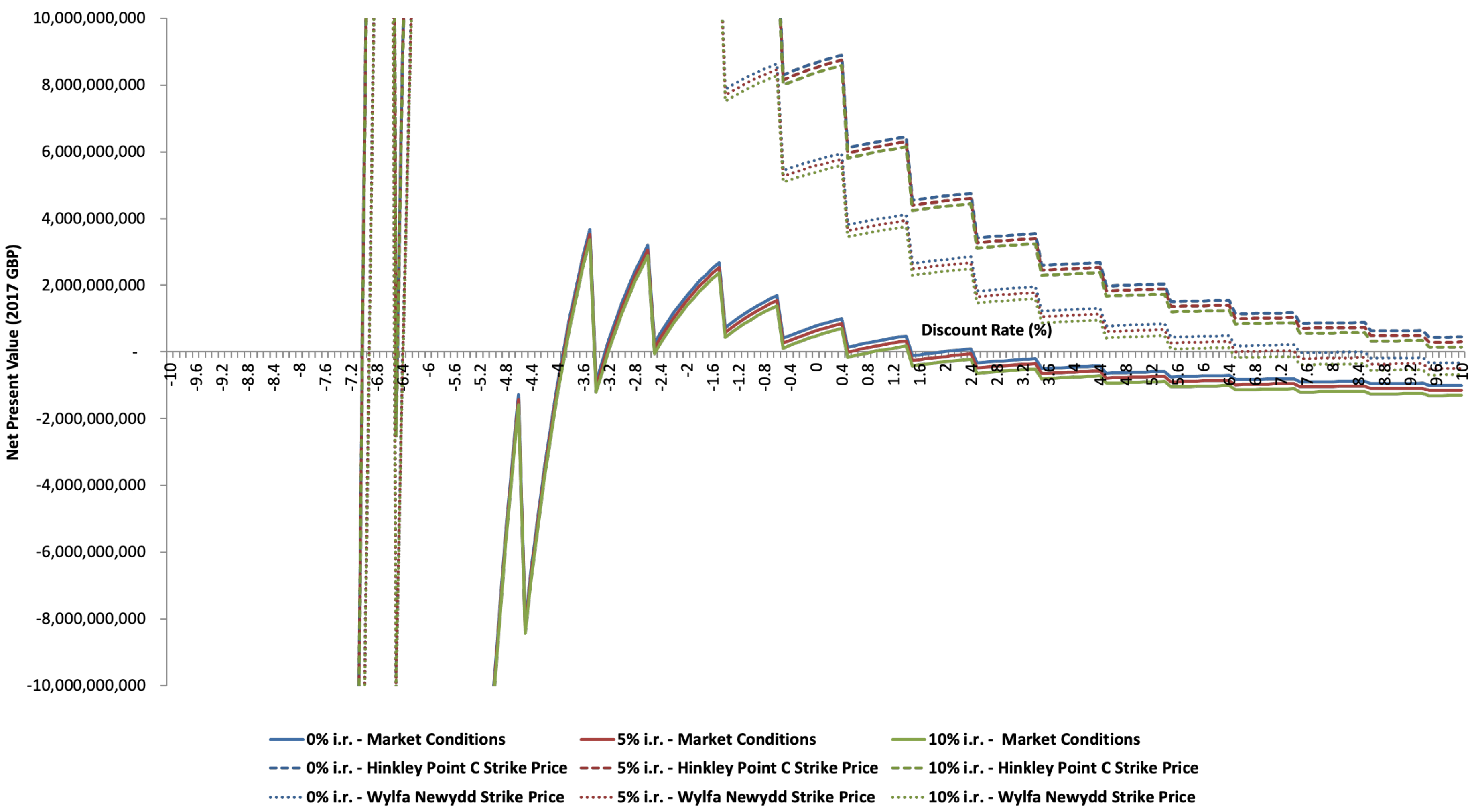

Figure 5.8: NPV estimates, as a function of discount rate, of NOAK & Nth On A Site SMRs working on an open fuel cycle basis and a 3 batch refuelling scheme, considering 0-10% interest rates.

Table 5.1: IRR central estimates of near term FOAK SMRs under normal market conditions and market intervention scenarios, at different interest rates and in a UK context.

IRR central estimates of FOAK SMRs following a 3-batch refuelling scheme.			
Interest Rate (%)	**IRR Market Conditions (%)**	**IRR Wylfa Newydd Strike Price (%)**	**IRR Hinkley Point C Strike Price (%)**
OPEN FUEL CYCLE			
0	-3.6, -3.5, -2.8, -2.6, -2.0, -1.4, -0.6	-6.7, -6.6, -6.2, **6.5**	-7.0, -6.5, -6.4, **8.6**
5	-3.6, -3.5, -2.8, -2.6, -1.9, -1.5, -0.7, -0.6	-6.7, -6.6, -6.2, **5.5**	-7.0, -6.5, -6.4, **7.5**
10	-3.5, -2.8, -2.6, -1.8, -1.5	-6.7, -6.6, -6.2, **4.5**	-7.0, -6.5, -6.4, **6.5**

Table 5.2: IRR central estimates of near term NOAK & 1st On A Site SMRs under normal market conditions and market intervention scenarios, at different interest rates and in a UK context.

IRR central estimates of NOAK & 1st On A Site SMRs following a 3-batch refuelling scheme.			
Interest Rate (%)	**IRR Market Conditions (%)**	**IRR Wylfa Newydd Strike Price (%)**	**IRR Hinkley Point C Strike Price (%)**
OPEN FUEL CYCLE			
0	-3.6, -3.5, -2.9, -2.6, -2.2, -1.4, -1.2, -0.5, 0, **0.4**	-6.7, -6.6, -6.2, **8.5**	-7.0, -6.5, -6.4, **>10**
5	-3.6, -3.5, -2.9, -2.5, -2.1, -1.4, -1.1, -0.5, **0.4**	-6.7, -6.6, -6.2, **7.5**	-7.0, -6.5, -6.4, **9.5**
10	-3.6, -3.5, -2.9, -2.6, -2.0, -1.5, -1.0, -0.6	-6.7, -6.6, -6.2, **6.5**	-7.0, -6.5, -6.4, **8.6**

Table 5.3: IRR central estimates of near term NOAK & Nth On A Site SMRs under normal market conditions and market intervention scenarios, at different interest rates and in a UK context.

IRR central estimates of NOAK & Nth On A Site SMRs following a 3-batch refuelling scheme.			
Interest Rate (%)	**IRR Market Conditions (%)**	**IRR Wylfa Newydd Strike Price (%)**	**IRR Hinkley Point C Strike Price (%)**
OPEN FUEL CYCLE			
0	-3.9, -3.4, -3.2, 1.5, 1.9, **2.4**	-6.9, -6.5, -6.4, **8.5**	-7.0, -6.5, >**10**
5	-3.9, -3.4, -3.2, 0.5, **1.5**	-6.9, -6.5, -6.4, **7.5**	-7.0, -6.5, >**10**
10	-3.9, -3.4, -3.2, -2.5, 0.5, 0.8, **1.3**	-6.9, -6.5, -6.4, **6.5**	-7.0, -6.5, >**10**

The interpretation of the IRR estimates of near term Integral Pressurised Water SMRs requires the understanding of multiple IRRs and negative IRRs. On one hand, an investment project can have as many IRRs as there are sign changes of the cash flows [203, 204]. Furthermore, in the case of multiple IRR, the IRR closest to the real cost of capital (or discount rate) is regarded as the 'true' IRR [204]. On the other hand, negative IRRs may be interpreted as net losses. Nonetheless, normally analysts are encouraged to disregard negative IRRs when preparing IRR averages, given that further quantitative analysis of negative IRRs is almost always meaningless [204]. In other words, given that the 'real' IRR is the one closest to the real cost of capital, one is not likely to deal with negative IRRs unless the corresponding real cost of capital is negative. However, this situation is very unlikely because the real cost of capital (or discount rate) is derived from the cost of equity and the cost of debt [205]. The rate of return demanded by investors, is almost certainly, always positive. Consequently, there are chances of dealing with negative costs of capital and, as a result, with negative IRRs only if the interest rate paid on a debt is negative. Apart from the attempt of the Swiss National Bank to deter investor inflows by weakening the Swiss Franc in 2015 with -0.75% interest rates, negative interest rates are not frequent [206, 207].

As a result, from Tables 5.1 - 5.3, near term FOAK SMRs are unlikely to be an attractive investment under typical UK market conditions, regardless of the cost of debt, if one assumes that the lack of positive IRRs indicates net losses. Later on, also under UK market conditions, NOAK-1st On A Site SMRs might be barely profitable with low interest rates and NOAK-Nth On A Site SMRs seem to be the most attractive investment option as they display the highest IRRs under UK market conditions. In contrast, if there is a market intervention or a government incentive, the IRRs of near term FOAK and NOAK SMRs are likely to be always around the typically assumed discount rates (5-10%) for nuclear projects. In fact, the UK's National Nuclear Laboratory (NNL) SMR Feasibility Study suggests that the IRR of SMR projects is likely to be less than 10%, most likely in the 7.5-8.5% range [17]. Moreover, regardless of strike price, the results presented above suggest that a particular SMR project becomes more attractive as one secures lower interest rates. Similarly, Tables 5.1 - 5.3 indicate that, for a given interest rate, it is reasonable to assume that the highest IRRs will be displayed by NOAK-Nth On A Site SMRs, followed by NOAK-1st On A Site SMRs and lastly by FOAK SMRs.

5.1.1.4 Return on Investment (ROI)

When the ROI is calculated for a time period of a year (e.g. considering average annual profit) it is equivalent to the annual growth rate or the annualised rate of return of a given investment. Thus, the higher the ROI the more attractive an investment becomes. In contrast with the IRR, the ROI does not account for differences in the value of money over time [208]. Consequently, particularly in the case of nuclear power projects, these financial figures are likely to be different due to the length of the projects and the effect of the time value of money that is neglected by the ROI. Nonetheless, the IRR and the ROI are both considered by companies and analysts for capital budgeting decisions. As a result, considering the central undiscounted cash flows estimated for a 300 MWe Integral Pressurised Water SMR, previously presented in Sections 4.2 - 4.7, central ROI estimates of FOAK and NOAK Integral Pressurised Water SMRs were calculated for cash inflows resulting from: central wholesale electricity market prices (48.77 £$/MWh$), Wylfa Newydd (89.39 £$/MWh$) strike price and Hinkley Point C strike price (104.39 £$/MWh$). Results are now presented below.

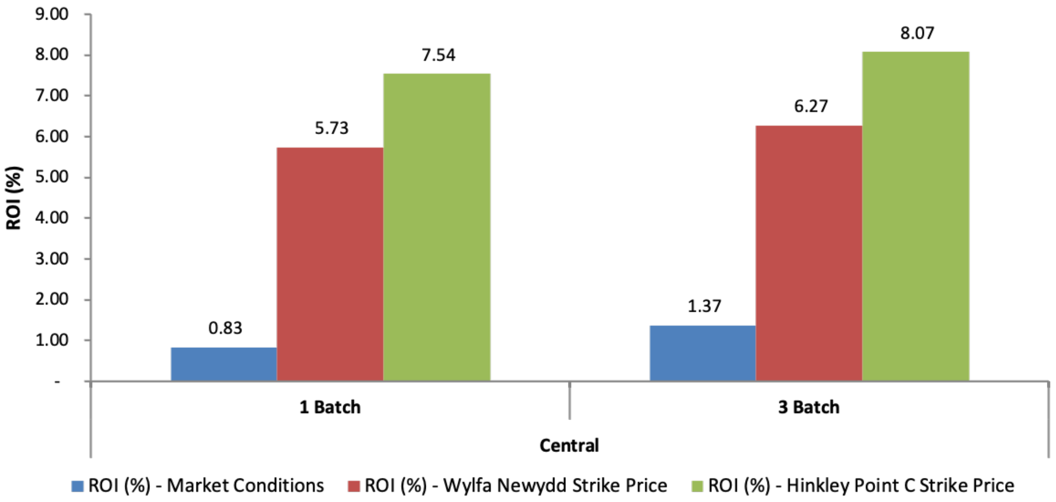

Figure 5.9: ROI estimates of FOAK SMRs working on an open fuel cycle basis.

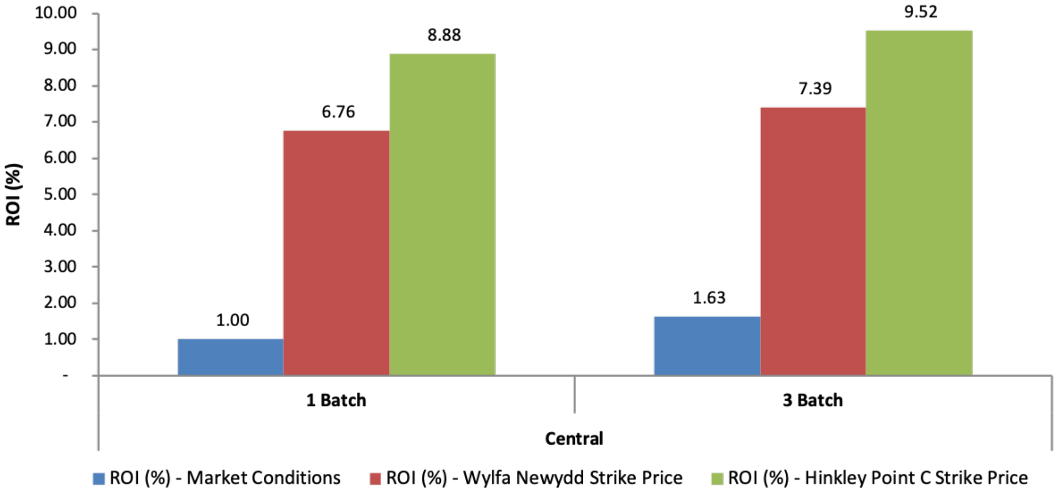

Figure 5.10: ROI estimates of NOAK & 1st On A Site SMRs working on an open fuel cycle basis.

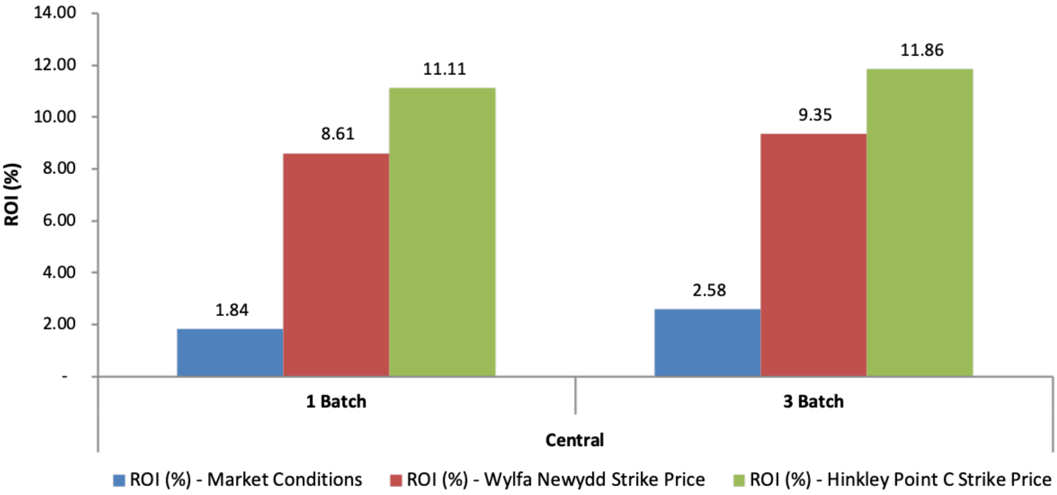

Figure 5.11: ROI estimates of NOAK & Nth On A Site SMRs working on an open fuel cycle basis.

On one hand, Figures 5.9 - 5.11 suggest that under British wholesale electricity market conditions SMRs could be slightly more competitive than their IRRs indicate. Nevertheless, the ROI carries more risk given that it does not consider levelised figures and, therefore, the conclusion remains the same: without any market intervention or government incentive, SMRs are likely to be barely profitable or not profitable at all. On the other hand, if there is some government incentive, SMRs could have similar IRR and ROI figures of approximately 5-10% depending on the scenario assessed. In particular, with the highest IRR and ROI figures, NOAK-Nth On A Site SMRs might be the most attractive investment project, followed by NOAK-1st On A Site SMRs and lastly by FOAK SMRs.

5.1.1.5 Payback Period

Recalling Subsection 3.2.1.5, the payback period is the time it takes for an investment to reach a breakeven point. Consequently, the desirability of an investment is inversely proportional to its payback period [71]. In relation, the payback period central estimates of 300 MWe Integral Pressurised Water SMRs were calculated taking advantage of the fact that the payback period is the inverse function of the ROI (expressed as a percentage) times a hundred (See Equations A.4 in Appendix A.4 and A.5 in Appendix A.5).

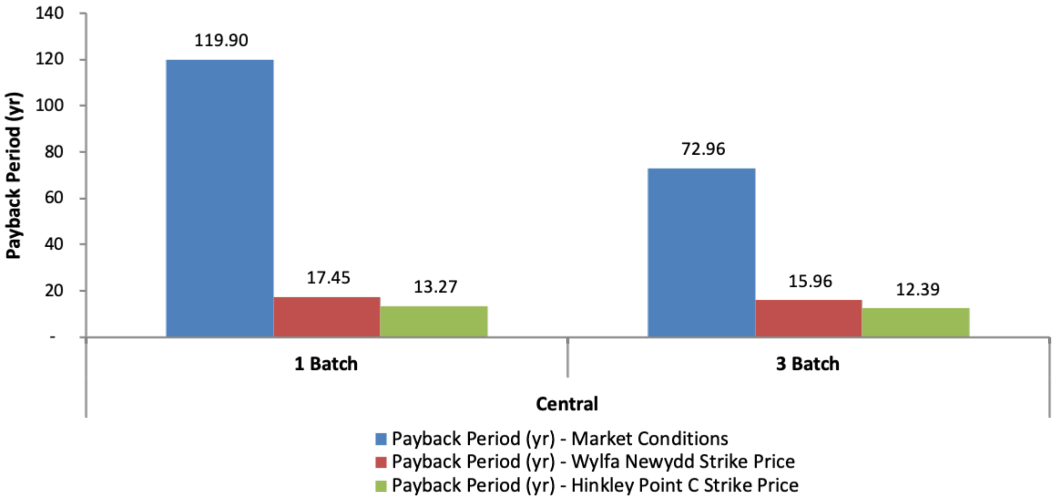

Figure 5.12: Payback period estimates of FOAK SMRs working on an open fuel cycle basis.

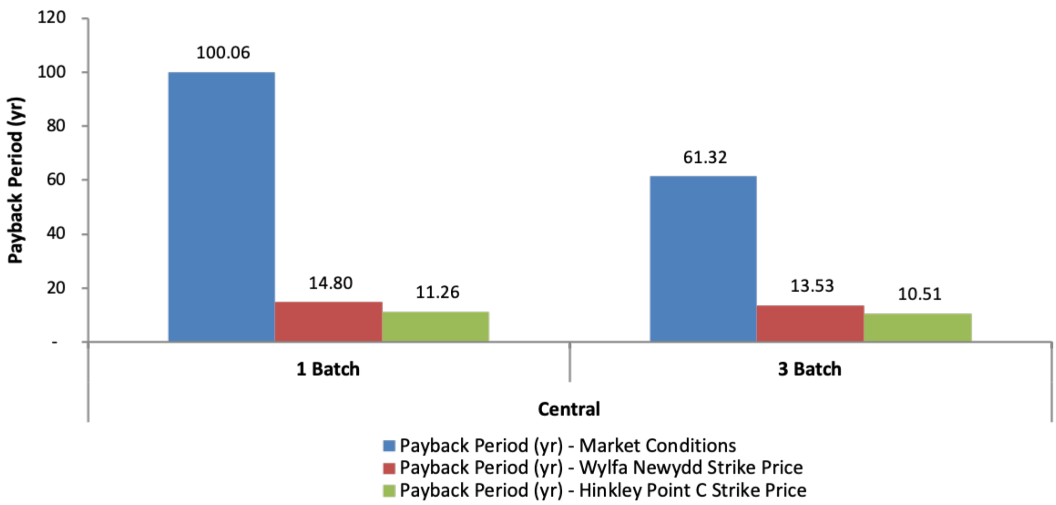

Figure 5.13: Payback period estimates of NOAK & 1st On A Site SMRs working on an open fuel cycle basis.

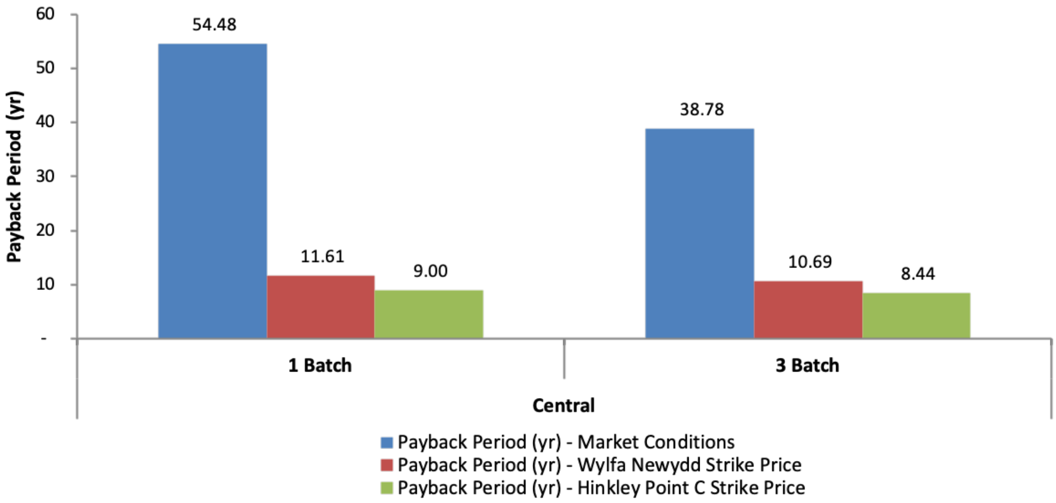

Figure 5.14: Payback period estimates of NOAK & Nth On A Site SMRs working on an open fuel cycle basis.

From Figures 5.12 - 5.14 and considering a 60 years operational lifetime, the payback period of near term SMRs is very likely to be excessively long, under typical market conditions. Regardless of the refuelling scheme, without government incentives or support, FOAK and NOAK-1st On A Site SMRs might never reach a breakeven point. In the case of NOAK-Nth On A Site SMRs, they would have payback periods of around 40-60 years which would be unacceptable for investors. In contrast, if the government absorbs part of the debt, NOAK-Nth On A Site SMRs could have payback periods as short as 9 years; NOAK-1st On A Site SMRs, 11 years and FOAK SMRs, 13 years. However, arguably not many firms are prepared to make an investment of the size required for SMRs and wait 9-13 years for a breakeven point.

5.1.1.6 Economic Dispatchability

In order to measure the economic drawback that near term SMRs could deal with if their capacity and availability was not fully utilised, the Economic Dispatchability (ED) of a representative 300 MWe Integral Pressurised Water SMR was estimated. For this estimation the levelised costs of the representative SMR, which were introduced in Sections 4.3-4.6, were used as inputs for Equation A.6 (See Appendix A.6). As a result, low, central and high scenarios were analysed considering low, central and high fuel cycle costs, 0-10% interest rates, 5-10% discount rates and 1-3 batch refuelling schemes. The results are presented next.

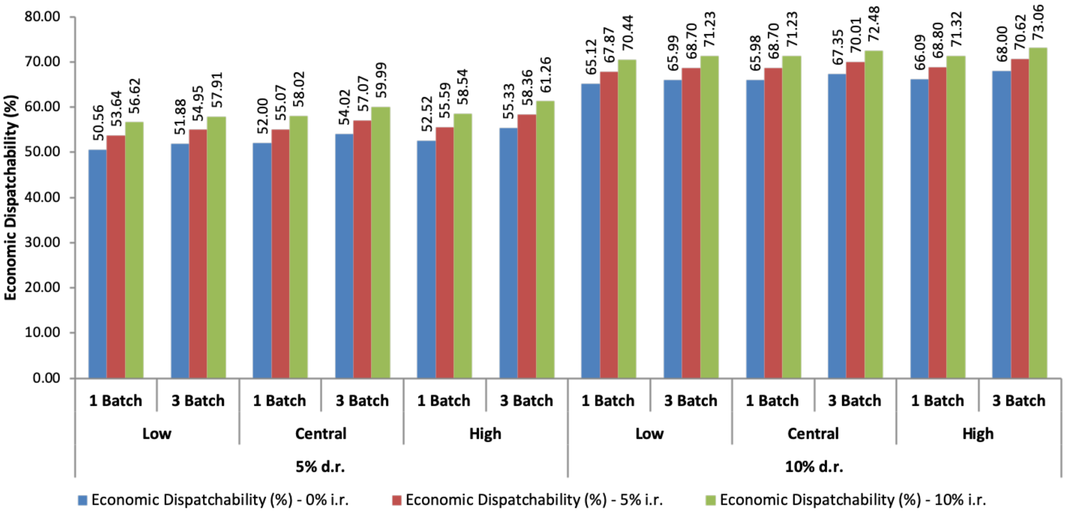

Figure 5.15: ED estimates of FOAK SMRs working on an open fuel cycle basis.

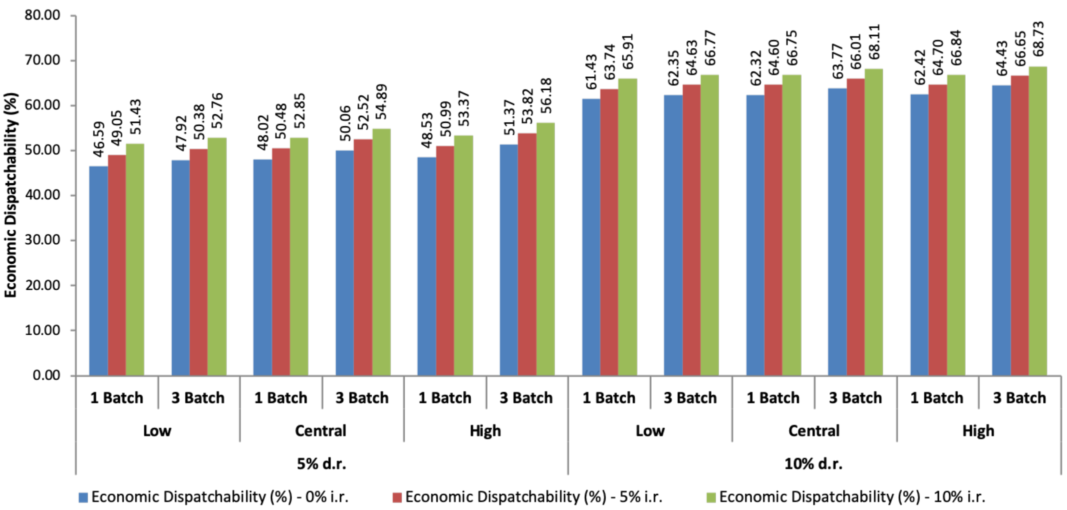

Figure 5.16: ED estimates of NOAK & 1st On A Site SMRs working on an open fuel cycle basis.

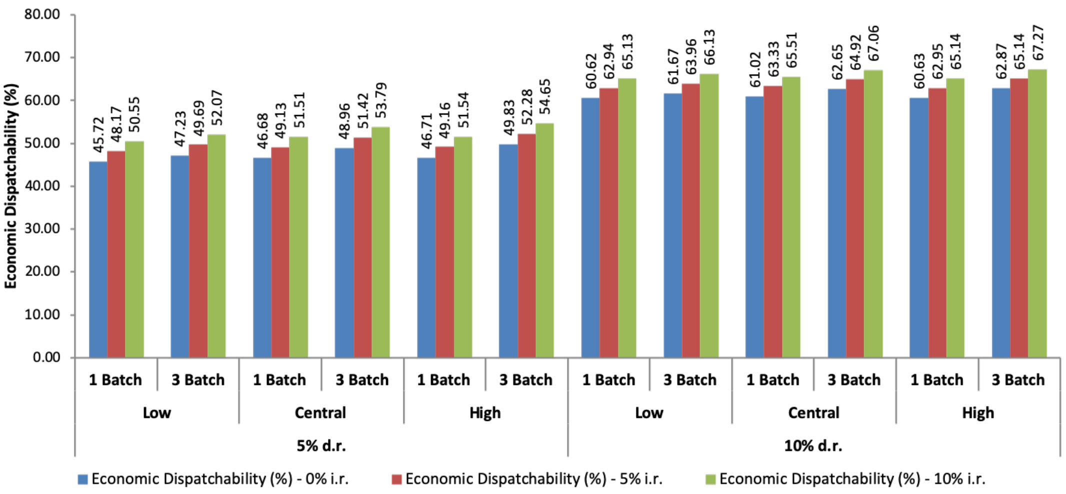

Figure 5.17: ED estimates of NOAK & Nth On A Site SMRs working on an open fuel cycle basis.

From Figures 5.15-5.17, conservative estimates indicate that, in the best case, at least half of the levelised cost of near term SMRs is likely to be attributed to its capital cost component. In particular, the economic dispatchability of SMRs could be between 50-73%, for FOAK SMRs; 47-69%, for NOAK-1st On A Site SMRs; and 46-67%, for NOAK-Nth On A Site SMRs. In other words, SMRs might only be an attractive investment if they are employed as a base load technology rather than a peak load technology.

5.1.2 Risk of Investment

5.1.2.1 Maturity of Technology

At first, in 2013, the UK's Government showed its interest in the potential benefits offered by SMRs in the Nuclear Industrial Strategy [209]. Later on, in 2016, the Government expressed an ambitious nuclear research and development programme accompanied by a £250 million investment and a competition to identify the most attractive SMR design for the UK [210]. As a result, on the 23th July 2019, the Government committed an £18 million initial fund to support the development of the SMR design proposed by the consortium led by Rolls-Royce (See Table 4.2 in Section 4.1 for more information). Furthermore, Rolls-Royce communicated that this support will be matched by contributions of the consortium, and third parties, in order to “mature the design, address the considerable manufacturing technology requirements and to progress the regulatory licensing process” [211]. Therefore, given that there are no licensed and commercially operational SMRs in the UK yet, which could validate their potential, SMRs are not a mature technology.

5.1.2.2 Corruption Perception Index (CPI)

Recalling Subsection 3.2.2.2, based on a 0 (highly corrupt) to 100 (very clean) scale, the CPI reflects the perceived level of public sector corruption. In relation, following the CPI2019, the organisation Transparency International foresees a crisis in democracy around the world. In CPI2019 more than two-thirds of the 180 countries assessed scored below 50 and, as a result, Transparency International recognises that most of the countries are failing to control corruption [212]. Nevertheless, out of the 180 countries, the UK (CPI2019: 77) shares the 12th place with Canada, Australia, and Austria in a rank where the first places, occupied by New Zealand and Denmark (CPI2019: 87), are the least corrupt countries and the last place, occupied by Somalia (CPI2019: 9), is the most corrupt country. As Table 5.4 illustrates, except for the 2019 fall from the 11th to the 12th place, the UK has consistently controlled corruption and it is ranked among the least corrupt countries in the world. In consequence, SMRs in the UK would be very low risk investment projects, in terms of losses due to corruption.

Table 5.4: Corruption Perception Index (CPI) Results 2019.
Source: [212]

Rank	**Country**	**2019**	**2018**	**2017**	**2016**	**2015**
1	New Zealand	87	87	89	90	91
1	Denmark	87	88	88	90	91
3	Finland	86	85	85	89	90
4	Switzerland	85	85	85	86	86
4	Singapore	85	85	84	84	85
4	Sweden	85	85	84	88	89
7	Norway	84	84	85	85	88
8	Netherlands	82	82	82	83	84
9	Luxembourg	80	81	82	81	85
9	Germany	80	80	81	81	81
11	Iceland	78	76	77	78	79
12	Canada	77	81	82	82	83
12	**United Kingdom**	**77**	**80**	**82**	**81**	**81**
12	Australia	77	77	77	79	79
12	Austria	77	76	75	75	76
180	Somalia	9	10	9	10	8

5.1.2.3 Long-term Sovereign Credit Ratings (Foreign and Local Currency)

Following the referendum in which the electorate voted for the UK to leave the European Union, on the 27th June 2016, S&P Global Ratings lowered the UK's long-term foreign and local currency credit ratings from ‘AAA’ to ‘AA’ with a negative outlook. In other words, due to a less predictable, stable and effective policy framework the UK went from ‘extremely strong capacity to meet financial commitments’ to ‘very strong capacity to meet financial commitments’ [213]. As of early-2020, the UK's long-term foreign and local currency credit ratings are still ‘AA’, but now they have a stable outlook [214]. In any case, the UK is still within the top 20 countries with the best credit ratings (See Table 5.5). Therefore, considering all the previous, the ‘AA’ rating, with stable outlook of the UK illustrates a very strong capacity to meet financial commitments, but also some degree of political instability that leads to less predictable growth prospects and external finances. Consequently, judging by its long-term sovereign credit ratings, the UK is still a good candidate for SMR investment projects. Nevertheless, in order to be the best candidate the UK has to provide a more secure environment for investment by bringing back political and economic stability.

Table 5.5: Top 20 Sovereign Credit Ratings as of Early-2020.
See Annex A.8 for Ratings Definitions / Source: [214]

Rank	**Country**	**Long-term Foreign Currency Rating / Outlook**	**Long-term Local Currency Rating / Outlook**
1	Liechtenstein	AAA / Stable	AAA / Stable
2	Sweden	AAA / Stable	AAA / Stable
3	Norway	AAA / Stable	AAA / Stable
4	Switzerland	AAA / Stable	AAA / Stable
5	Luxembourg	AAA / Stable	AAA / Stable
6	Singapore	AAA / Stable	AAA / Stable
7	Denmark	AAA / Stable	AAA / Stable
8	Germany	AAA / Stable	AAA / Stable
9	Canada	AAA / Stable	AAA / Stable
10	Australia	AAA / Stable	AAA / Stable
11	Netherlands	AAA / Stable	AAA / Stable
12	Hong Kong	AA+ / Stable	AA+ / Stable
13	Finland	AA+ / Stable	AA+ / Stable
14	United States	AA+ / Stable	AA+ / Stable
15	Austria	AA+ / Stable	AA+ / Stable
16	New Zealand	AA / Positive	AA+ / Positive
17	Korea	AA / Stable	AA / Stable
18	France	AA / Stable	AA / Stable
19	**United Kingdom**	**AA / Stable**	**AA / Stable**
20	Belgium	AA / Stable	AA / Stable

5.2 Techno-Economic Assessment

5.2.1 Affordability of Energy Services

5.2.1.1 Levelised Cost of Electricity (LCOE)

Upon direct application of Equation B.1 (See Appendix B.1) and using the estimated discounted cash outflows of a 300 MWe Integral Pressurised Water SMR (See Sections 4.3-4.6) the LCOE of near term SMRs was estimated for low, central and high scenarios. The three scenarios reflect low, central and high prices of the whole electricity generation chain. Furthermore, 0-10% interest rates, 5-10% discount rates and 1-3 refuelling schemes were considered. The results are presented next.

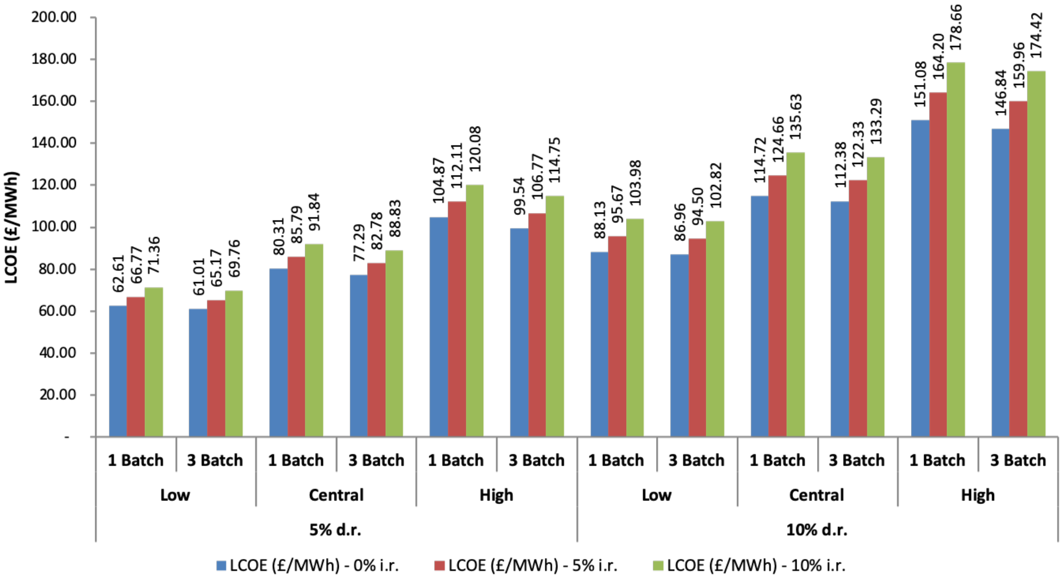

Figure 5.18: LCOE estimates of FOAK SMRs working on an open fuel cycle basis.

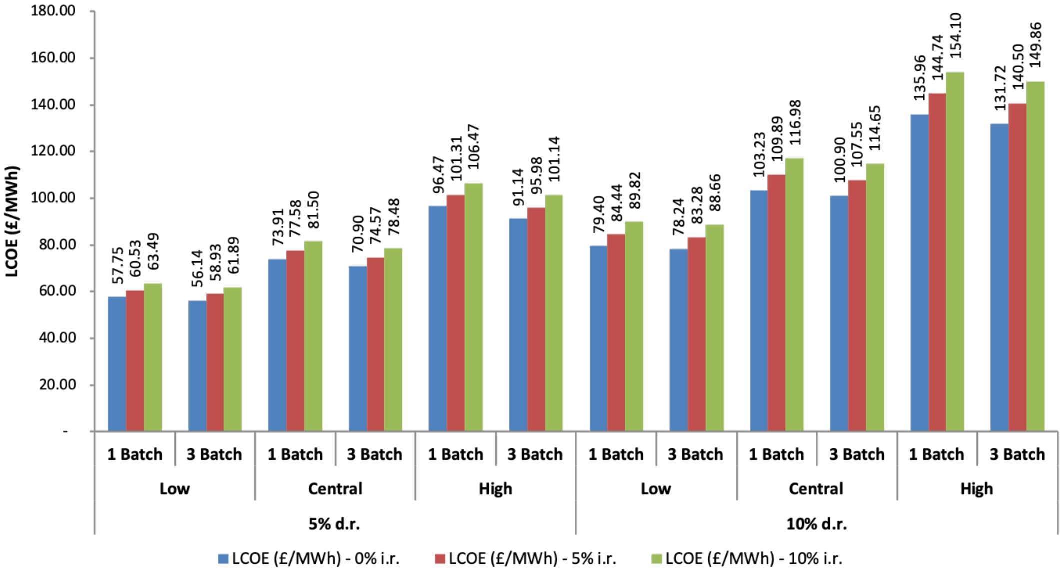

Figure 5.19: LCOE estimates of NOAK & 1st On A Site SMRs working on an open fuel cycle basis.

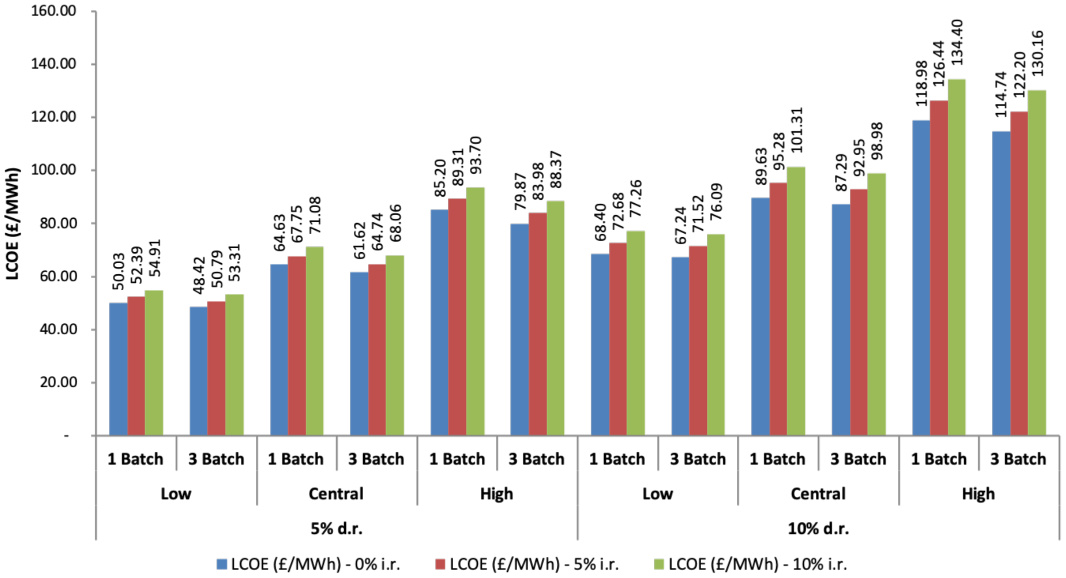

Figure 5.20: LCOE estimates of NOAK & Nth On A Site SMRs working on an open fuel cycle basis.

From Figures 5.18 - 5.20, the average price of electricity that consumers would have to pay for the investor to break even and repay all the costs incurred by owning and operating a power plant through the lifetime of the power plant would be between 62-180 $£/MWh$, for FOAK SMRs, 58-155 $£/MWh$ for NOAK-1st On A Site SMRs and 50-135 $£/MWh$ for NOAK-Nth On A Site SMRs depending on the scenario assessed. In relation, both the interest rate and the discount rate are directly proportional to the LCOE and, therefore, small interest and discount rates lead to small LCOEs while high interest and discount rates result in high LCOEs. Similarly, according to Figures 5.18 - 5.20, FOAK SMRs would display the highest LCOEs and NOAK-Nth On A Site SMRs would offer the lowest LCOEs.

The LCOE is probably the only sustainability indicator published by SMR reactor vendors or stakeholders. Consequently, the accuracy and validity of the LCOE and, therefore, of other sustainability indicators presented in this report can be verified upon comparison of the results presented above with other LCOE estimations. In relation, the UK's National Nuclear Laboratory (NNL) was granted access to data from leading SMR designs and made an LCOE analysis based on these [17]. On one hand, based on all the SMR designs studied, the NNL found that near term SMRs might have an LCOE of around 102.2-139.7 $£/MWh$ considering 5-10% discount rates, respectively. On the other hand, considering mature designs only, the NNL estimated an LCOE of 62-101.2 $£/MWh$. Similarly, considering that SMRs with 3-batch refuelling schemes seem to be the most economically attractive and also assuming the 10% interest rate normally applied to the private sector, Figures 5.18 and 5.19 suggest that FOAK SMRs could have an LCOE of 88.83-133.29 £/MWh while NOAK SMRs might have an LCOE of 78.48-114.65 £/MWh considering 5-10% discount rates. The slight differences between the NNL results and the results presented in this study can be easily explained by the fact that the NNL results "do not reflect deployment in any specific country and could be significantly different in the UK market" [17]. In any case, the similarity between the results here presented and those estimated by the NNL enhances the validity of the attractiveness of investment and economic sustainability indicators presented in this study.

5.2.1.2 Fuel Price Sensitivity Factor (FPSF)

Similar to the LCOE calculation (See Subsection 5.2.1.1 above), utilising a representative 300 MWe Integral Pressurised Water SMR and its discounted cash outflows (See Sections 4.3-4.6) the FPSF of near term SMRs was estimated for low, central and high scenarios, considering 1-3 batch refuelling schemes. As a result, from Figures 5.21-5.23, it was found that the FPSF for FOAK SMRs might be within the 1.05-1.20 range, 1.06-1.22 for NOAK-1st On A Site SMRs and 1.06-1.25 for NOAK-Nth On A Site SMRs, depending on the scenario and conditions assessed. As the capital expenditure decreases with NOAK SMRs their fuel cost remains constant and, therefore, the fuel cost share of the LCOE increases. Nonetheless, in any case, the impact of a doubling in fuel prices on the LCOE of SMRs is likely to be relatively small.

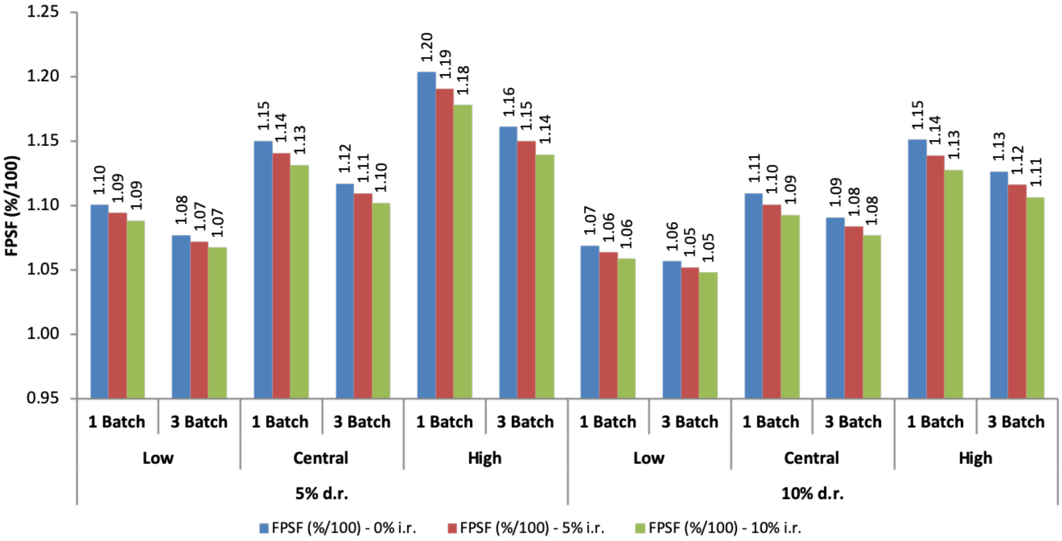

Figure 5.21: FPSF estimates of FOAK SMRs working on an open fuel cycle basis.

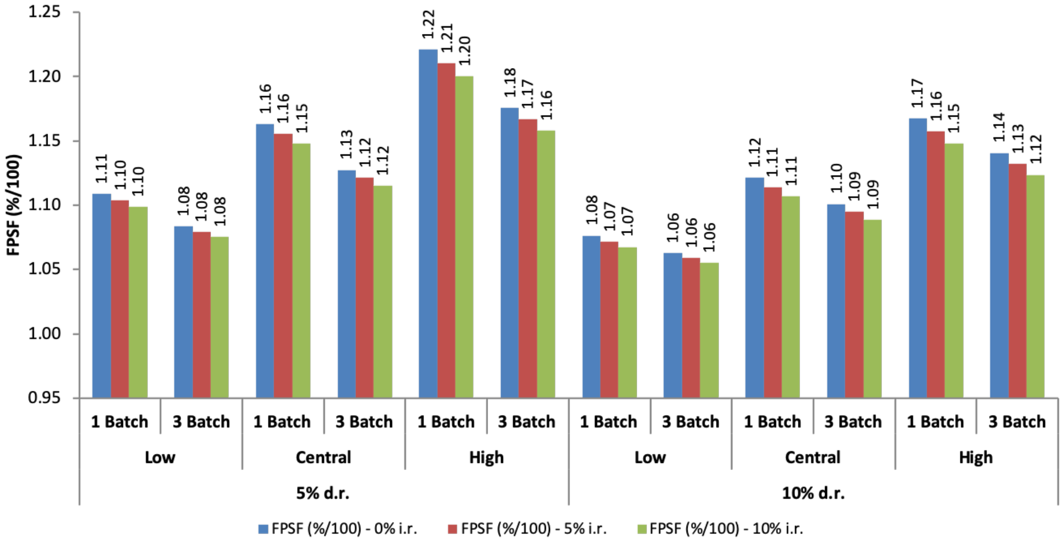

Figure 5.22: FPSF estimates of NOAK & 1st On A Site SMRs working on an open fuel cycle basis.

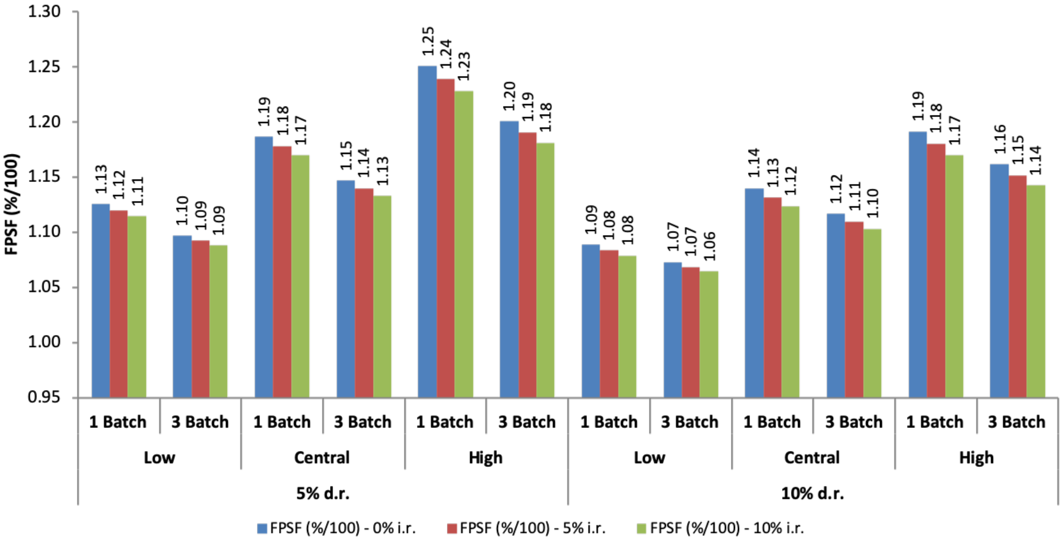

Figure 5.23: FPSF estimates of NOAK & Nth On A Site SMRs working on an open fuel cycle basis.

5.2.2 Reliability and State of Technology

5.2.2.1 Capacity Factor

On one hand, as discussed previously in Subsection 4.4.2.2, throughout techno-economic assessments, a standard capacity factor of 85-90% is normally assumed for large scale nuclear [80, 153, 166]. On the other hand, there seems to be no reason to believe that SMRs could have lower capacity factors than the large scale reactors from which they are derived [168]. In fact, according to the specifications and designs of near term SMRs [126, 127, 128, 175, 180, 181], SMRs might be able to deliver capacity factors of 90-95%

or more. In other words, SMRs could be more reliable than large scale nuclear, coal and combined-cycle natural gas power plants which are normally assumed, by consensus, to have capacity factors of 85% [80]. Finally, recalling Subsection 3.3.2.1, it is worth to mention that a fair cross technology comparison will only compare technologies of similar nature (base load (e.g. nuclear, coal and combined-cycle natural gas power plants) or intermittent generators (e.g. renewables)). Consequently, it is unfair to compare the possible 90-95% capacity factor of SMRs with the 25-35% capacity factor of wind energy [64], as these technologies are of different operational nature.

5.2.2.2 Availability Factor

By convention, it is normally assumed that large nuclear reactors operate at high availability factors of around 85-90% [168]. Nonetheless, in recent years, availability factors of over 90% have been achieved and, therefore, availability factors of ≈95% are likely to be achieved by reactors under development [68]. In relation, some techno-economic assessments like [168] or [194] assume that SMRs will have slightly higher availability factors than large nuclear reactors. In fact, SMR vendors claim that their designs will achieve >95% availability factors [126]. In consequence, in theory, SMRs could offer almost uninterrupted availability of electricity supply.

5.2.2.3 Average Ramp Rate

Technical constraints (e.g. thermomechanical stresses induced on the fuel cladding and some structural components) limit the power ramping of a nuclear reactor. In relation, the power ramping of most large reactors in operation is limited to less than 5% of P_{max} per minute [113]. Nevertheless, due to the European Utility Requirements, all new reactors must now be able to achieve ≈5% of P_{max} per minute. Moreover, the ability to load follow improves with low core power densities and shorter cores and, therefore, SMRs (PWR-based) could offer better power ramping than large reactors. In fact, some reactor vendors claim that SMRs could potentially achieve 10% of P_{max} per minute average ramp rates. Nonetheless, pellet cladding interaction at high power ramp rates and power stability concerns still need to be investigated. As a result, as demonstrated by the technical specifications of near term SMRs (e.g. [128]), SMRs are expected to be at least as capable as large reactors (5% of P_{max} per minute) [168].

5.2.2.4 Average Response Time

The cycling parameters (minimum up time and minimum down time) allocated to a power plant may reflect not only technical constraints (e.g. the time required to synchronise a generator with the frequency of the grid), but also economic constraints (e.g. minimum up times, imposed by the operator, to reduce the cost of start-ups and shutdowns). In relation, large scale nuclear reactors are commonly assumed to have average response times (average of minimum up and minimum down times) of around 24 hours [215]. Similarly, according to [168] SMRs are likely to have average response times of several days. In fact, the technical specifications of near term SMRs indicate that SMRs could have average response times between 24 and 36 hours [126]. Therefore, in terms of average response times, SMRs might have similar cycling parameters to those of large reactors.

5.2.2.5 Reserves-to-Production (R-P) Ratio

Typical large scale reactors and near term SMRs share the same vulnerability to physical interruptions of primary fuel supply (uranium). Furthermore, given that worldwide conventional uranium economically recoverable reserves have grown faster than the annual production rate of uranium, the global R-P ratio of conventional uranium has grown at a steady rate for several decades as shown below in Figure 5.24. While it was 71 years[44] in 1986, latest resources/production figures suggest that the global R-P ratio of conventional uranium is approximately 149 years[45] [85, 87].

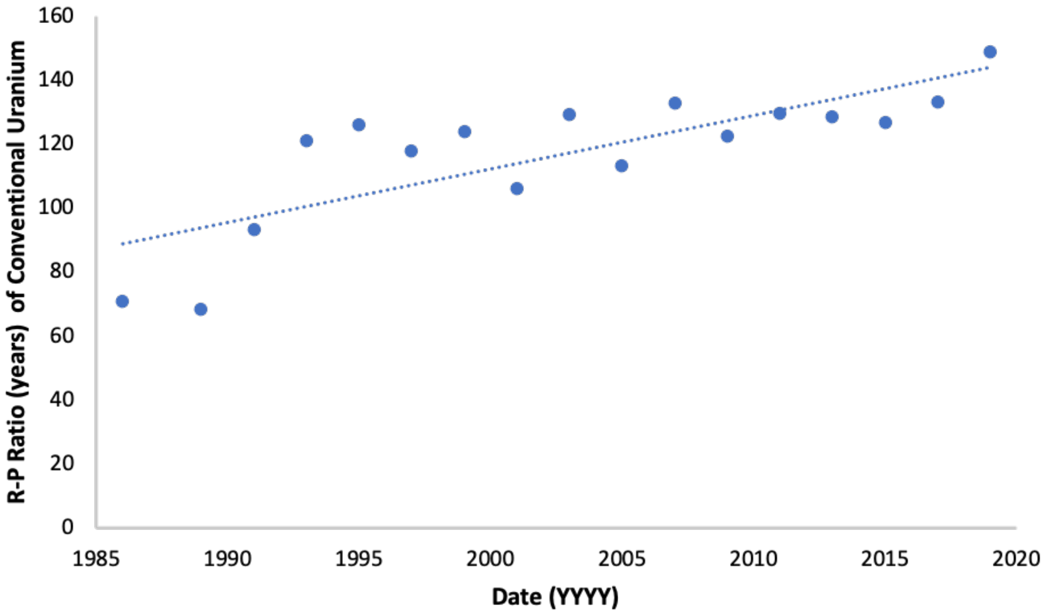

Figure 5.24: Historical evolution of the R-P ratio of conventional uranium. Source: [85, 86, 87, 216, 217, 218, 219, 220]

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[44] Reserves as of 1986: $4,414,000\ tU$ / Production as of 1986: $62,249\ tU/yr$ [87].

[45] Reserves as of 2019: $8,070,400\ tU$ / Production as of 2019: $54,224\ tU/yr$ [85].

5.3 Single and Multiple (4) SMRs vs. Large Reactors

Table 5.6: Attractiveness of Investment and Techno-Economic Sustainability Central Estimates of Single and Multiple (4) SMRs Relative to Single Large PWRs.
Considerations: Open Fuel Cycle, 3-Batch Refuelling Scheme, 10% interest rate and 5% discount rate.

Category	**Issue Addressed**	**Indicator**	**Single SMR vs. LR**	**4 SMRs vs. LR**
Attractiveness of Investment	Financial Figures of Merit	Size of Investment (£/MWe)	+16%	-10%
		NPV (£/MWe)	-58% to -36%	-26% to -18%
		IRR	-32% to -14%	-21% to -5%
		ROI	-39% to -36%	-28% to -25%
		Payback Period	+56% to +64%	+33% to +38%
		Economic Dispatchability	-14%	-18%
	Risk of Investment	Maturity of Technology	Not Mature	Not Mature
		CPI	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Local Currency	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Foreign Currency	No Difference	No Difference
Techno-Economic	Affordability of Energy Services	LCOE	+27%	+11%
		FPSF	+2%	+4%
	Reliability and State of Technology	Capacity Factor	Up to +10 Percentage Points	Up to +10 Percentage Points
		Availability Factor	Up to +10 Percentage Points	Up to +10 Percentage Points
		Average Ramp Rate	≥0 Percentage Points	≥0 Percentage Points
		Average Response Time	No Difference	No Difference
		R-P Ratio	No Difference	No Difference

Expanding the test case 4 SMRs vs. 1 LR - Scenario B (4 NOAK SMRs) - introduced in Chapter 4, the estimated cash flows of 4 SMRs were used to evaluate the attractiveness of investment and techno-economic sustainability of multiple SMRs. In relation, the same methodology used in the previous sections of this Chapter to calculate the attractiveness of investment and economic sustainability of a single SMR was followed. However, in this case, an appropriate construction schedule where the first year of construction of a subsequent SMR coincide with the second construction year of the immediately previous SMR was considered. Similarly, the cash flows of large PWRs assumed throughout Chapter 4 were utilised to estimate the attractiveness of investment and techno-economic sustainability benchmark figures of large reactors. Consequently, in order to put in context the main findings of this chapter and to provide a full attractiveness of investment and economic sustainability analysis of single and multiple near term SMRs, the relevant indicators of single and multiple near term SMRs were compared against those of typical large reactors (See Table 5.6 above).

On one hand, from Table 5.6, central estimates indicate that some degree of uncertainty will be unavoidably linked to near term SMRs, single or multiple, given that they are not a proven technology. Moreover, results suggest that SMRs have very little chance of competing with the cost-efficiency of large reactors, on a one to one basis. In contrast, multiple SMR configurations are likely to display financial figures of merit comparable to those of large reactors. In fact, multiple SMRs might require a smaller investment per unit capacity than large reactors. In other words, multiple SMRs will almost certainly be able to compete with the attractiveness of investment of large reactors due to the exploitation of co-siting economies and the time value of money. Investments on single SMRs could only be justified if the size of investment, in absolute terms (£) was a limitation or if larger reactors were not suitable for the location of interest.

On the other hand, also from Table 5.6, both single and multiple SMR configurations could have higher capacity factors, higher availability factors and higher average ramp rates than typical large scale reactors. However, single SMRs could have up to 30% higher LCOEs while the levelised cost per unit electricity of multiple SMRs might only be around 10% higher than that of large reactors. Therefore, it is fair to say that although SMRs are likely to be slightly more exposed to primary fuel price changes than large reactors, single and multiple SMR configurations will most certainly have better techno-economic sustainability figures than typical large scale reactors even with higher

LCOEs. Particularly, multiple SMRs not only could achieve higher capacity factors, higher availability factors and higher average ramp rates than large reactors, but also they have strong chances of offering competitive electricity prices due to the similarity of their LCOE with that of typical large scale reactors.

5.3.1 The Factory-Built Factor

By definition, SMRs are meant to be built in factories as modules to minimise costly on-site construction [122, 123]. However, as briefly discussed in Subsection 4.2.4.3, the 1.4-4% overnight cost reduction due to modularisation suggested by reference [129] and assumed throughout this study does not account for the 'factory-built factor'. This has led to the conclusion that single SMRs are unlikely to compete with the attractiveness of investment of large scale reactors unless a significant overnight cost reduction due to construction in a factory environment is demonstrated. In consequence, the magnitude of such a 'factory-built factor' necessary for single SMRs to compete with the attractiveness of investment of large scale reactors was investigated. As a result, it was found that a 32% overnight cost reduction due to construction in a factory environment would be sufficient to bring the LCOE of single SMRs down to 89.39 $£/MWh$ (Wylfa Newydd's strike price), which has been assumed to be the highest strike price likely to be awarded by the UK Government in the near future. As shown below in Table 5.7, a 'factory-built factor' of this size would make single SMRs as attractive as large reactors, while multiple SMRs would become a more attractive investment than large scale nuclear. Finally, this 32% overnight cost reduction due to the 'factory-built factor' would not affect the superiority of single and multiple SMRs over typical large scale reactors in terms of techno-economic sustainability.

Table 5.7: Attractiveness of Investment and Techno-Economic Sustainability Central Estimates of Single and Multiple (4) SMRs Relative to Single Large PWRs. Considerations: **32% Overnight Cost Reduction due to Construction in a Factory Environment**, Open Fuel Cycle, 3-Batch Refuelling Scheme, 10% interest rate and 5% discount rate.

Category	**Issue Addressed**	**Indicator**	**Single SMR vs. LR**	**4 SMRs vs. LR**
Attractiveness of Investment	Financial Figures of Merit	Size of Investment (£/MWe)	-22%	-39%
		NPV (£/MWe)	-5% to -1%	+9% to +15%
		IRR	No Difference	Up to +5%
		ROI	-10% to -5%	+7% to +11%
		Payback Period	+6% to +11%	-10% to -7%
		Economic Dispatchability	-29%	-33%
	Risk of Investment	Maturity of Technology	Not Mature	Not Mature
		CPI	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Local Currency	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Foreign Currency	No Difference	No Difference
Techno-Economic	Affordability of Energy Services	LCOE	+5%	-8%
		FPSF	+4%	+6%
	Reliability and State of Technology	Capacity Factor	Up to +10 Percentage Points	Up to +10 Percentage Points
		Availability Factor	Up to +10 Percentage Points	Up to +10 Percentage Points
		Average Ramp Rate	≥0 Percentage Points	≥0 Percentage Points
		Average Response Time	No Difference	No Difference
		R-P Ratio	No Difference	No Difference

5.4 Chapter Summary

Attractiveness of Investment and Economic Sustainability of Small Modular Reactors in a UK Scenario

- **Unique Contribution:** The attractiveness of investment and the techno-economic sustainability of single and multiple SMRs were measured upon evaluating a relevant set of indicators. Similarly, results were compared with the corresponding benchmark figures of large reactors, which were also estimated in the present study. Consequently, main findings are presented relative to the attractiveness of investment and techno-economic sustainability of typical large scale reactors.

  Attractiveness of Investment of near term SMRs

  - Single SMRs have very little chances to compete with the attractiveness of investment of large reactors unless a 32% overnight cost reduction due to construction in a factory environment is demonstrated. Therefore, if no further cost reductions are validated, single SMRs are unlikely to be chosen over large reactors unless the size of investment is a limitation or if the location of interest is unsuitable for large reactors.
  - Multiple SMRs with a cumulative capacity equivalent to that of large reactors will most certainly compete with the attractiveness of investment of large reactors.

  Techno-Economic Sustainability of near term SMRs

  - Single and multiple SMR configurations will be slightly more exposed to primary fuel price changes, multiple SMRs a little more than single SMRs. Nonetheless, in any case, both SMR configurations are highly likely to be more techno-economically sustainable than typical large scale reactors due to their potentially higher capacity factors, availability factors and average ramp rates.
  - In particular, due to the similarity with the LCOE of large reactors, multiple SMRs are the most techno-economically sustainable of the three nuclear energy technologies, followed by single SMRs and lastly by large reactors.

Chapter 6

SPECIAL CASE: MICRO NUCLEAR REACTORS (MNRs)

As established in Section 4.1, in a UK context, the term SMRs is reserved for LWRs with output power capacities of up to 300 MWe, while small modular non-LWRs are known as Advanced Modular Reactors (AMRs). In relation, with rated capacities under 30 MWe and 100 $MWth$, micro nuclear reactors (MNRs) are typically not water cooled or water moderated and, therefore, they are categorised as AMRs rather than SMRs. In general, MNR designs are high temperature gas reactors (HTGRs), liquid metal cooled fast reactors or molten salt reactors. Furthermore, MNRs are expected to compete in different market niches compared to SMRs: 1) Standby/emergency generators for critical infrastructure (e.g. nuclear power plants, data centres, military sites, oil and gas terminals, etc.), 2) remote and off-grid locations, and 3) autonomous facilities for major energy users (e.g. steel works, desalination, chemical sites, etc.). The size of the MNR global market has been estimated as of around 2850 MWe by 2030 [221].

Compared to SMRs, MNRs are expected to exploit further the benefits of an integral design due to their smaller size. Influencing the capital cost, assembly work on site is meant to be completely eliminated by manufacturing single large functional units in factory environments. Regarding O&M costs, MNRs are designed to minimise on-site presence during operation and to execute emergency shutdowns with no operator intervention [221]. In terms of fuel, in general, MNR designs consider the utilisation of TRISO compacts rather than typical fuel pellets. Moreover, while SMR designs are targeting 3-batch to whole core refuelling schemes with 2-4 years refuelling intervals, MNR designs are aiming for half core to whole core refuelling schemes with 2-5 years and potentially up to 10 years refuelling intervals [221, 222, 223]. In contrast with SMRs ($\leq$5% enrichment), in order to achieve these refuelling schemes, MNRs will require nuclear fuel with up to 15-20% enrichment levels [222, 223]. Finally, with operational lifetimes of 60 years, it should be possible to remove MNRs from site with minimum onsite dismantling and take them to specialised facilities for decommissioning [221].

6.1 Economic Characterisation of Micro Nuclear Reactors in a UK Scenario

There is little publicly available financial information regarding MNRs and, therefore, it is yet unknown how the previously mentioned technical features will affect or benefit MNR economics. Nonetheless, comparing the limited MNR economic assessments with the SMR economics, presented in previous sections, and assuming economies of scale the economics of a representative 10 $MWth$ (4 MWe) High Temperature Gas Micro Nuclear Reactor (HTGMNR) were estimated. Furthermore, the specifications of this hypothetical reactor match those of the only UK MNR design, the U-Battery, except that this representative 4 MWe MNR would have a half core refuelling scheme rather than the whole core refuelling scheme of the U-Battery [224]. Consequently, the economics of this hypothetical 4 MWe HTGMNR should portray the economics of near term MNRs in a UK scenario, without considering possible cost reductions that could result from whole core refuelling schemes.

6.2 Generation Costs

To begin with the economic analysis of the HTGMNR of interest, it was assumed that for a given capacity there would be a linear combination of the cost components of integral pressurised water SMRs that would be equivalent to the total cost of high temperature gas reactors (HTGRs) with the same capacity (See Equation 6.1). In relation, as identified and translated to English by [225], [226] estimated the total cost per unit capacity of the GTHTR300 Japanese 300 MWe HTGR design, with a half core refuelling scheme, and presented his findings per cost component relative to the costs of a large scale PWR. As a result, upon direct comparison of [226] findings with the cost estimations of a 300 MWe SMR, presented in previous sections, the corresponding constants were identified ($C_1 = 0.65$, $C_2 = 0.39$, $C_3 = 0.65$, $C_4 = 4.84$). Moreover, due to the methodology followed, these constants are a numerical representation of the technology and refuelling scheme differences between near term pressurised water SMRs and small scale HTGRs with the same capacity. In other words, the application of the refined cost-to-capacity method and the transformation constants should, in principle, allow us to estimate the costs of an HTGR within the SMRs capacity range ($\leq$300 MWe).

$$\begin{aligned} TC_{HTGR}(N) = C_1 \times K_{SMR}(N) + C_2 \times O\&M_{SMR}(N) \\ + C_3 \times F_{SMR}(N) + C_4 \times D_{SMR}(N) \end{aligned} \tag{6.1}$$

Where:

- $TC_{HTGR}(N)$: Total cost of a N MWe HTGR (£).
- $K_{SMR}(N)$: Capital cost of a N MWe SMR (£).
- $O\&M_{SMR}(N)$: Operation and maintenance cost of a N MWe SMR (£).
- $F_{SMR}(N)$: Fuel cost of a N MWe SMR (£).
- $D_{SMR}(N)$: Decommissioning cost of a N MWe SMR (£).
- $C_{1,\ldots,4}$: Transformation constants.

It could be tempting to first estimate the cost of a 4 MWe integral pressurised water reactor using the refined cost-to-capacity method and then convert these figures to those of the desired 4 MWe high temperature gas reactor using the transformation constants. Nonetheless, any cost estimation provided by the refined cost-to-capacity method used for the SMR analysis, previously presented, is only valid for reactor capacities greater or equal to 300 MWe. Cost capacity curves are only valid piecewise as the extent of economies of scale is different for different capacity ranges and technologies [135]. As specified in Sections 4.2,4.4 and 4.6, the output elasticity ranges utilised for overnight, O&M and decommissioning costs have only been supported for the 300-1300 MWe range.

Engineers, agencies and vendors concluded in the 1970s that economies of scale seemed to be more pronounced in the lower rating range than in the higher rating range for nuclear power plants [135]. In contrast, in 1976, the econometric studies of [227] showed that economies of scale were weaker for low reactor capacities. Moreover, [227] also suggested that technological change can dramatically change cost-capacity curves. As a consequence, the extent of economies of scale for nuclear reactors with capacities smaller than 300 MWe was investigated using 1) the LCOE of a 300 MWe HTGR (71.04 £$/MWh$) which was calculated applying the transformation constants to the estimated cost components of a 300 MWe integral pressurised water SMR, 2) the LCOE of the 165 MWe ESKOM HTGR design (56 £$/MWh$) [228], and 3) the LCOE of the 4 MWe U-Battery design (116 £$/MWh$) [224]. Assuming that these estimations were all calculated considering similar operational lifetimes, it can be shown that the cost-capacity curve of HTGRs with capacities smaller than 300 MWe suggests an output elasticity of total cost of approximately 0.9. To put this in perspective, according to the cost component output elasticities reported in sections 4.2, 4.4, 4.5 and 4.6, PWRs in the 300-1300 MWe range have a weighted average output elasticity of total cost of around 0.7. Consequently, if what MNR stakeholders claim to be true is true, it was found that economies of scale are weaker for HTGRs in the 0-300 MWe range than for PWRs in the 300-1300 MWe range.

It was assumed that the difference between the output elasticities of total cost of 300-1300 MWe PWRs (0.7) and 0-300 MWe HTGRs (0.9) is proportional to the difference between the output elasticities, by cost component, of the two reactor technologies within the corresponding capacity ranges, except for the output elasticity of fuel cost which was assumed to be unity in both cases. In other words, except for fuel cost, this study suggests that the output elasticities by cost component of HTGRs (0-300 MWe) could be around 30% larger than those of PWRs (300-1300 MWe): output elasticity of overnight cost = 0.5-1, output elasticity of O&M cost = 0.8-0.9, and output elasticity of decommissioning cost = 0.9-1. It is worth mentioning that the output elasticities were limited to one in the cases where a 30% increment resulted in diseconomies of scale (output elasticity >1). Consequently, the economics of a 4 MWe HTGMNR, most likely with a half core refuelling scheme and 2-5 years refuelling intervals, were estimated as follows. First, the costs of a 300 MWe integral pressurised water SMR were estimated by using the refined cost-to-capacity method (See Subsections 4.2.4-4.6) to escalate down the costs of a ~1200 MWe PWR. Then the transformation constants, presented above, were applied to transform the costs of the 300 MWe integral pressurised water SMR to those of a 300 MWe HTGR. Finally, the costs of a 4 MWe HTGMNR were estimated scaling down the costs of the 300 MWe HTGR using the cost-to-capacity method, but considering the output elasticities, previously presented, derived for HTGRs in the 0-300 MWe range and assuming a linear behaviour for the fuel cost-capacity curve. The whole methodology is schematically presented next in Figure 6.1. Similarly, the estimated cost components of a NOAK-1st On A Site 4 MWe HTGMNR, with TRISO compacts, a half core refuelling scheme and an open fuel cycle, are presented in Tables 6.1-6.4. These results are followed by a comparison of central NOAK MNR cost estimates with those of NOAK pressurised water SMRs and typical large scale reactors in Figures 6.2-6.5.

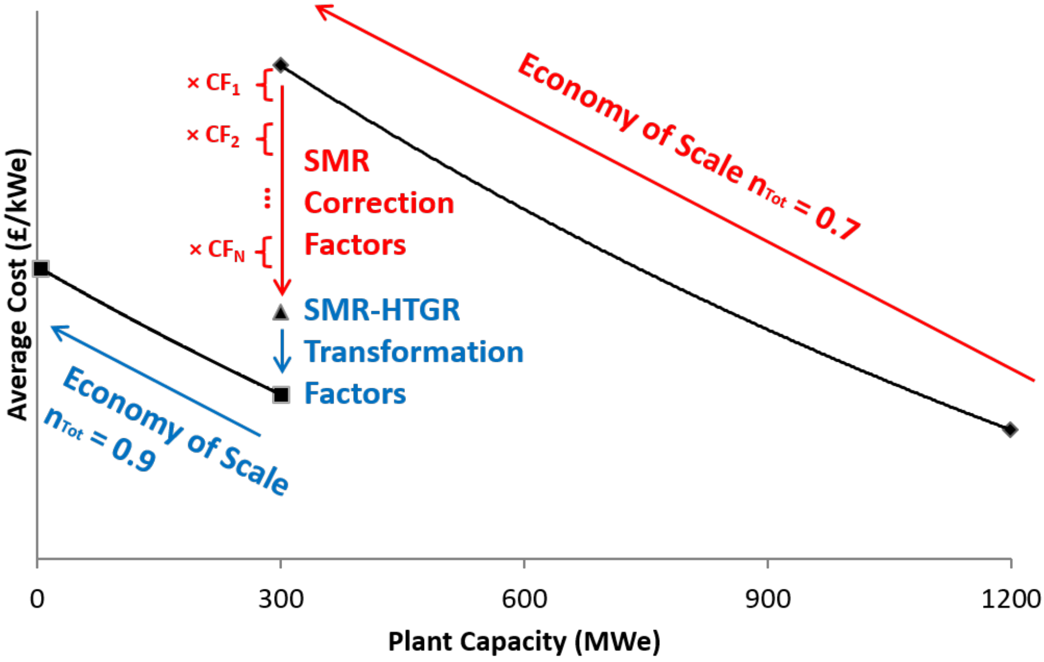

Figure 6.1: Schematic Representation of the methodology used to calculate the Average Costs of a representative 4 MWe MNR.

Table 6.1: Average Overnight Cost of a NOAK & First On A Site 4 MWe High Temperature Gas Micro Nuclear Reactor.

FOAK LR vs. NOAK-First On A Site SMR & MNR Average Overnight Cost (£/kWe)			
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe)	4,469		
Cost-to-Capacity Factor	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85		
Modular Construction Correction Factor	× 0.99		
Construction in Series Correction Factor	× 0.85		
Cumulative Correction Factor	×1.64	×1.24	×0.94
Overnight Cost SMR (2017 GBP/kWe)	7,336	5,562	4,216
SMR-HTGR Transformation Factor	× 0.65		
MNR Output Elasticity of Overnight Cost (n_{oc})	0.5	0.8	1
MNR Cost-to-Capacity Factor	×7.94	×2.59	×1
MNR Cumulative Correction Factor	×5.13	×1.67	×0.65
Overnight Cost MNR (2017 GBP/kWe)	37,615	9,281	2,721

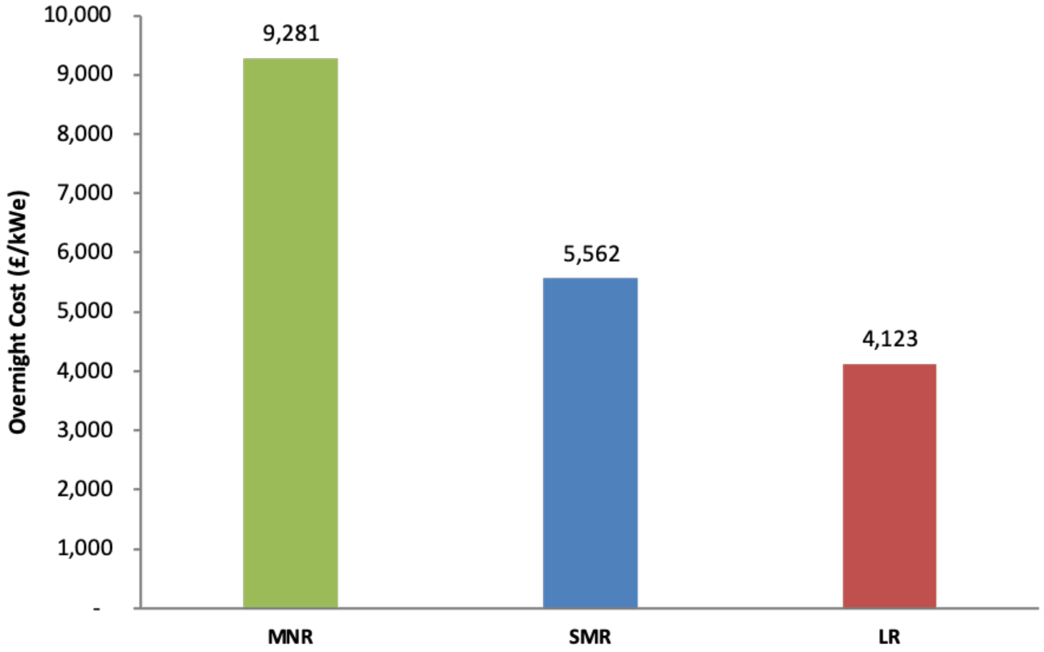

Figure 6.2: Central Overnight Cost Estimates of NOAK-First On A Site MNRs, SMRs and Typical Large Scale Nuclear.
Source for Large Scale Nuclear: [17]

Table 6.2: Average O&M Cost of a NOAK & First On A Site 4 MWe High Temperature Gas Micro Nuclear Reactor.

FOAK LR vs. NOAK-First On A Site SMR & MNR Average O&M Cost (£/kWe)						
Output Elasticity of O&M Cost (n_{OM})	0.6	0.65	0.7	0.6	0.65	0.7
Undiscounted O&M Cost of Reference Plant (2017 GBP/kWe)	7,486					
Cost-to-Capacity Factor	×1.74	×1.62	×1.51	×1.74	×1.62	×1.51
Operational Learning Correction Factor	× 0.995					
Cumulative Correction Factor	×1.73	×1.62	×1.51	×1.73	×1.62	×1.51
Undiscounted O&M Cost SMR (2017 GBP/kWe)	12,961	12,094	11,285	12,961	12,094	11,285
SMR-HTGR Transformation Factor	× 0.39					
MNR Output Elasticity of O&M Cost (n_{OM})	0.8	0.85	0.9	0.8	0.85	0.9
MNR Cost-to-Capacity Factor	×2.59	×1.95	×1.47	×2.59	×1.95	×1.47
MNR Cumulative Correction Factor	×1.02	×0.77	×0.58	×1.02	×0.77	×0.58
Undiscounted O&M Cost MNR (2017 GBP/kWe)	13,184	9,292	6,549	13,184	9,292	6,549
Discount rate (%)	5			10		
Discounted O&M Cost MNR (2017 GBP/kWe)	4,367	3,078	2,169	2,409	1,698	1,197

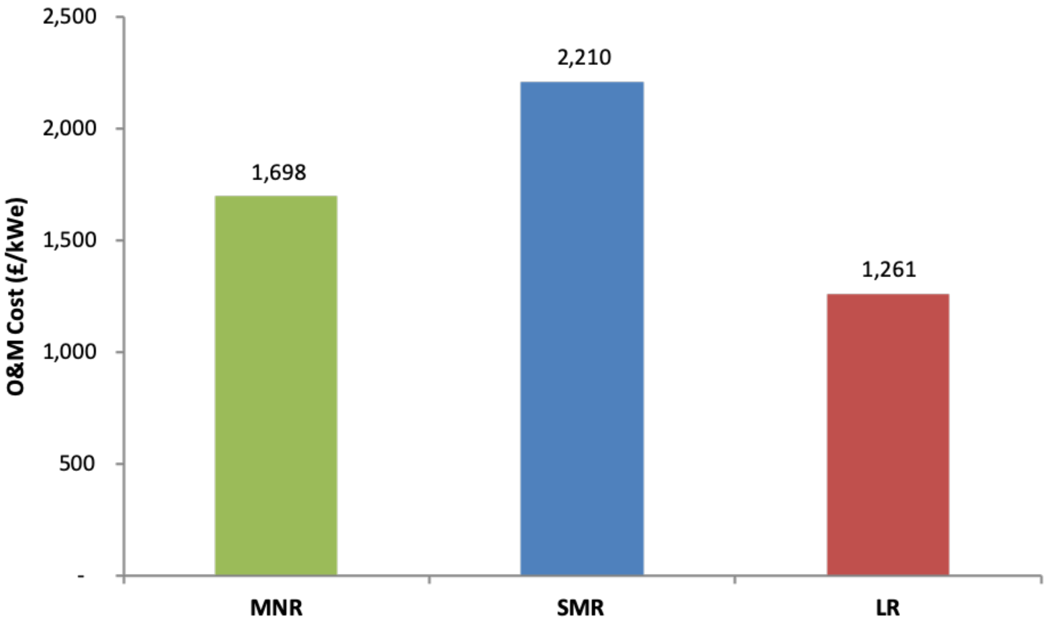

Figure 6.3: Central O&M Discounted Cost Estimates of NOAK-First On A Site MNRs, SMRs and Typical Large Scale Nuclear, considering a 10% discount rate. Source for Large Scale Nuclear: [153].

Table 6.3: Average Fuel Cost of a FOAK/NOAK 4 MWe High Temperature Gas Micro Nuclear Reactor. Open Fuel Cycle and Half Core Refuelling Scheme.

FOAK/NOAK MNR **Average Fuel Cost (£/kWe) - Open Fuel Cycle - Half Core Refuelling Scheme**						
Fuel Cycle Cost Scenario	Low	Central	High	Low	Central	High
Uranium Purchase	280	893	2,457	280	893	2,457
Conversion	28	68	110	28	68	110
Enrichment	213	733	1,074	213	733	1,074
Fabrication	413	413	413	413	413	413
Spent Fuel Transport and Storage	345	345	345	345	345	345
Encapsulation and Disposal	915	915	915	915	915	915
Undiscounted Fuel Cost MNR (2017 GBP/kWe)	2,193	3,367	5,314	2,193	3,367	5,314
Discount rate (%)	5			10		
Uranium Purchase	100	318	876	65	208	573
Conversion	12	29	46	8	20	32
Enrichment	86	297	435	59	203	297
Fabrication	165	165	165	110	110	110
Spent Fuel Transport and Storage	79	79	79	32	32	32
Encapsulation and Disposal	38	38	38	3	3	3
Discounted Fuel Cost MNR (2017 GBP/kWe)	479	925	1,638	277	575	1,047

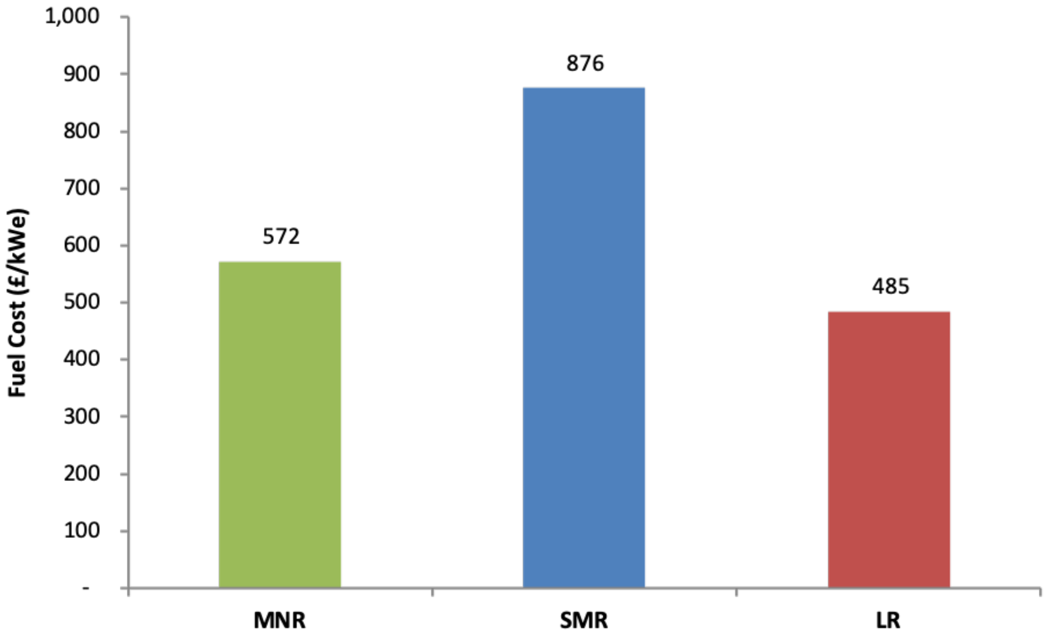

Figure 6.4: Central Fuel Discounted Cost estimates of FOAK/NOAK MNRs, SMRs and Typical Large Scale Nuclear, considering a 10% discount rate.
Source for Large Scale Nuclear: [153].

Table 6.4: Average Decommissioning Cost of a FOAK/NOAK & First On A Site 4 MWe High Temperature Gas Micro Nuclear Reactor.

FOAK/NOAK Large Reactor vs. FOAK/NOAK-First On A Site SMR & MNR Average Decommissioning Cost (£/kWe)						
Output Elasticity of Decommissioning Cost (n_{Decomm})	0.7	0.8	0.9	0.7	0.8	0.9
Undiscounted Decommissioning Cost of Reference Plant (2017 GBP/kWe)	345					
Cost-to-Capacity Factor	×1.51	×1.32	×1.15	× 1.51	×1.32	×1.15
Modular and Integral Design	×0.84					
Cumulative Correction Factor	×1.27	×1.11	×0.96	×1.27	×1.11	×0.96
Undiscounted Decommissioning Cost SMR (2017 GBP/kWe)	440	383	333	440	383	333
SMR-HTGR Transformation Factor	×4.84					
MNR Output Elasticity of Decommissioning Cost (n_{Decomm})	0.9	1	1	0.9	1	1
MNR Cost-to-Capacity Factor	×1.47	×1	×1	× 1.47	×1	×1
MNR Cumulative Correction Factor	×7.14	×4.84	×4.84	×7.14	×4.84	×4.84
Undiscounted Decommissioning Cost MNR (2017 GBP/kWe)	3,139	1,853	1,614	3,139	1,853	1,614
Discount rate (%)	5			10		
Discounted Decommissioning Cost MNR (2017 GBP/kWe)	1,040	614	535	574	339	295

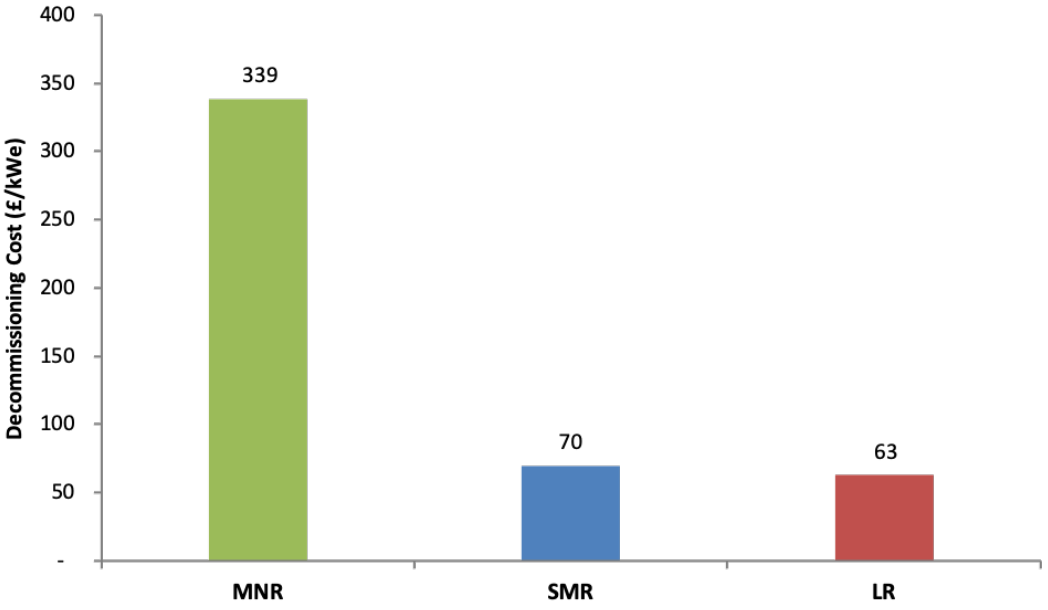

Figure 6.5: Central Discounted Decommissioning Cost Estimates of FOAK/NOAK MNRs, SMRs and Typical Large Scale Nuclear, considering a 10% discount rate. Source for Large Scale Nuclear: [191]

From Figures 6.2-6.5, even with a highly integrated design, MNRs could have an average overnight cost (£/kWe) around 67% and 125% higher than that of SMRs and LRs, respectively. Nonetheless, it is important to remember that the overnight cost does not include the interest paid during construction. In contrast, by minimising onsite presence during operation, the average O&M cost (£/kWe) of MNRs might be 23% lower than that of SMRs and 35% higher than that of typical large scale PWRs. Similarly, regardless of the implications of a highly enriched fuel, the TRISO fuel technology could result in competitive average fuel costs for MNRs. Results suggest that the average fuel cost (£/kWe) of MNRs is likely to be 35% lower than that of SMRs and only 18% higher than large scale PWRs. In relation, the limited information publicly available regarding the economics of MNRs (e.g. [225, 226]) suggests that the average fuel cost (£/kWe) of MNRs could be comparable to that of large scale PWRs due to a higher fuel burnup and a higher plant efficiency. In contrast, as mentioned in Subsection 4.5.1, smaller reactor cores are normally associated with poorer neutron economies and, therefore, with higher fuel costs per kWe. In other words, although publicly available literature (e.g. [225, 226]) suggests that MNRs could have a fuel cost per kWe similar to that of LRs, it is unclear how could MNRs overcome the poorer neutron economy of a smaller reactor core. As a result, it is acknowledged that the fuel cost estimates of MNRs presented in this study (Table 6.3 and Figure 6.4) carry a high degree of uncertainty and must be updated as more information regarding the fuel costs of MNRs becomes available. Finally, the methodology followed for this study indicates that the average decommissioning cost (£/kWe) of MNRs might be four times higher than that of SMRs and large scale PWRs. According to [225], the higher decommissioning cost of MNRs could be explained by the fact that the number of systems and structures that become radioactive during operation, and must be disposed during decommissioning, are bulkier in MNRs than in SMRs and large PWRs.

6.3 Cash Inflow

In order to calculate the cash inflows of a 4 MWe HTGMNR the electricity prices paid by non-domestic consumers were investigated. In contrast with SMRs, MNRs are intended to be owned directly by the electricity consumer and not by electricity generation companies. On one hand, large scale electricity generation companies (e.g. EDF Energy) usually sell the electricity to distribution/supply companies (e.g. EON) at wholesale electricity market prices (~50 £/MWh). Later on, electricity distribution companies sell the electricity to the public at retail prices which account for transmission losses. Consequently, the economic attractiveness of nuclear reactors with capacities equal or greater than 300 MWe has to be assessed from an electricity generation company (e.g. EDF Energy) point of view and, therefore, considering wholesale electricity prices. These reactors (≥300 MWe) exceed by far the power generation required by single non-domestic electricity consumers. On the other hand, a 4 MWe nuclear reactor has an annual generation capacity (~35,040 MWh) that falls within the annual consumption range of a large non-domestic electricity consumer (20,000 - 69,999 MWh), as defined by the UK's Department for Business, Energy & Industrial Strategy (DBEIS) [229]. In other words, a 4 MWe HTGMNR is likely to be owned by large companies in order to satisfy their own electricity needs. Consequently, to evaluate the economic attractiveness of a 4 MWe HTGMNR the cash inflows have to be estimated considering the money that a company would save by not paying retail electricity prices, over the lifetime of the nuclear reactor, to electricity distribution companies.

According to DBEIS's prices of fuels purchased by non-domestic consumers in the UK [229], large non-domestic consumers paid 104.41 £/MWh in 2017 and an average electricity price of 96 £/MWh during the period 2006-2018, in 2017 prices (See Figure 6.6). It must be noted that these electricity prices are comparable with the 104.39 £/MWh Hinkley Point C strike price. Therefore, it is safe to assume that a large non-domestic electricity consumer would pay an electricity price equal to Hinkley Point C strike price. Thus, the total cash inflow of a 4 MWe HTGMNR was calculated assuming a constant electricity price of 104.39 £/MWh over a 60 years operational lifetime, assuming constant electrical capacity (4 MWe), a constant 90% capacity factor and 5-10% discount rates in order to allow for cross technology comparison with pressurised water SMRs and large scale PWRs under similar scenarios. The results are shown below in Table 6.5.

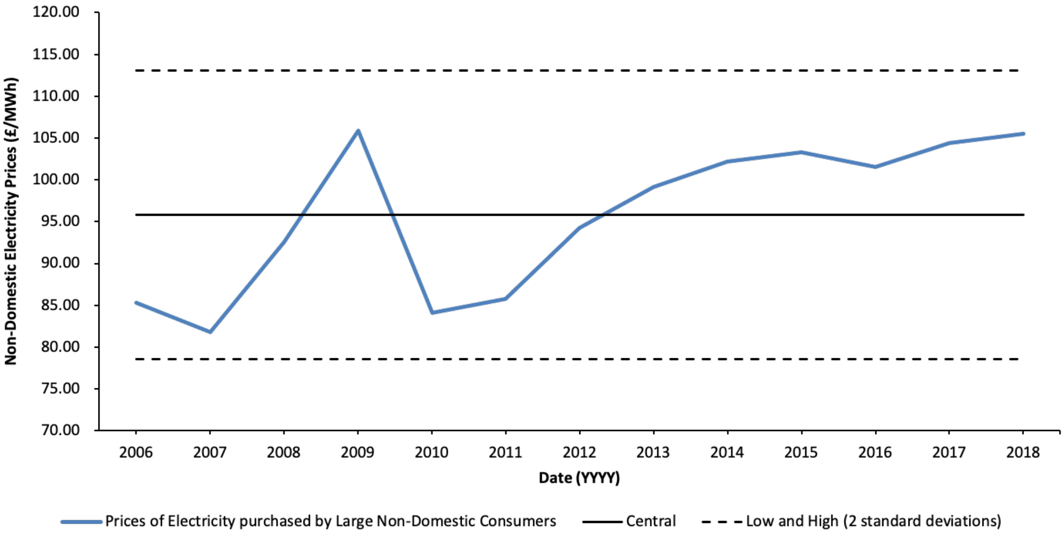

Figure 6.6: Derivation of Long Term Low, Central and High Electricity Prices paid by Large Non-Domestic Consumers.
Data Source: [229]

Table 6.5: Lifetime Cash Inflow of a 4 MWe High Temperature Gas MNR.
Figures quoted in 2017 prices.

Retail Price of Electricity (£/MWh)	**Undiscounted Value (£)**	**5% Discount Rate (£)**	**10% Discount Rate (£)**
104.39	197,522,582	65,431,838	36,093,542

6.4 Attractiveness of Investment

Utilising the estimated cash flows of a 4 MWe NOAK-1st On A Site HTGMNR, presented in Sections 6.2 and 6.3, the attractiveness of investment of MNRs is now analysed below upon evaluating the corresponding financial figures of merit and risk of investment indicators. Moreover, results are presented together with equivalent figures of SMRs and typical large PWRs in order to allow for cross technology comparison. In relation, NOAK-1st On A Site SMR data was taken from Section 5.1. Furthermore, large NOAK PWR figures were calculated using the typical NOAK PWR generation costs presented independently in Subsections 4.2.4.4, 4.4.2.3, 4.5.1 and 4.6.2.3, and estimating the corresponding cash inflows assuming a 60 years operational lifetime, an 85% capacity factor and Hinkley Point C Strike Price (104.39 £/MWh). In all cases, figures are meant to be UK specific.

6.4.1 Financial Figures of Merit

6.4.1.1 Size of Investment

On one hand, SMRs are expected to have construction periods of 3-4 years or less [128]. Therefore, in order to calculate the size of investment of NOAK SMRs, in Section 4.3 it was assumed that the overnight cost of NOAK SMRs would be evenly distributed among a 3 years construction period. On other hand, the differences between SMR and MNR construction schedules are not likely to be extensive [221]. Consequently, the size of investment required for NOAK MNRs, in a UK context, was estimated assuming that their overnight cost (See Section 6.2) would be evenly distributed among a 2 years construction period and considering 5-10% interest rates. Results are presented below in Table 6.6. Moreover, Figures 6.7 and 6.8 illustrate how the size of investment per unit capacity of NOAK-1st On A Site MNRs could differ from that of NOAK-1st On A Site SMRs and large PWRs.

Table 6.6: Estimated Size of Investment of a NOAK & First On A Site 4 MWe High Temperature Gas Micro Nuclear Reactor.

FOAK Large Reactor vs. NOAK-First On A Site SMR & MNR Size of Investment (£/kWe)						
Output Elasticity of Overnight Cost (n_{oc})	0.4	0.6	0.8	0.4	0.6	0.8
Overnight Cost of Reference Plant (2017 GBP/kWe**)**	4,469					
Cost-to-Capacity Factor	×2.30	×1.74	×1.32	×2.30	×1.74	×1.32
Design Improvement Correction Factor	× 0.85					
Modular Construction Correction Factor	× 0.99					
Construction in Series Correction Factor	× 0.85					
Cumulative Correction Factor	×1.64	×1.24	×0.94	×1.64	×1.24	×0.94
Overnight Cost SMR (2017 GBP/kWe**)**	7,336	5,562	4,216	7,336	5,562	4,216
SMR-HTGR Transformation Factor	× 0.65					
MNR Output Elasticity of Overnight Cost (n_{oc})	0.5	0.8	1	0.5	0.8	1
MNR Cost-to-Capacity Factor	×7.94	×2.59	×1	×7.94	×2.59	×1
MNR Cumulative Correction Factor	×5.13	×1.67	×0.65	×5.13	×1.67	×0.65
Overnight Cost MNR (2017 GBP/kWe**)**	37,615	9,281	2,721	37,615	9,281	2,721
Interest rate (%)	5			10		
Interest During Construction MNR (2017 GBP/kWe**)**	2,868	708	208	5,830	1,438	422
Size of Investment MNR (2017 GBP/kWe**)**	40,483	9,988	2,929	43,445	10,719	3,143

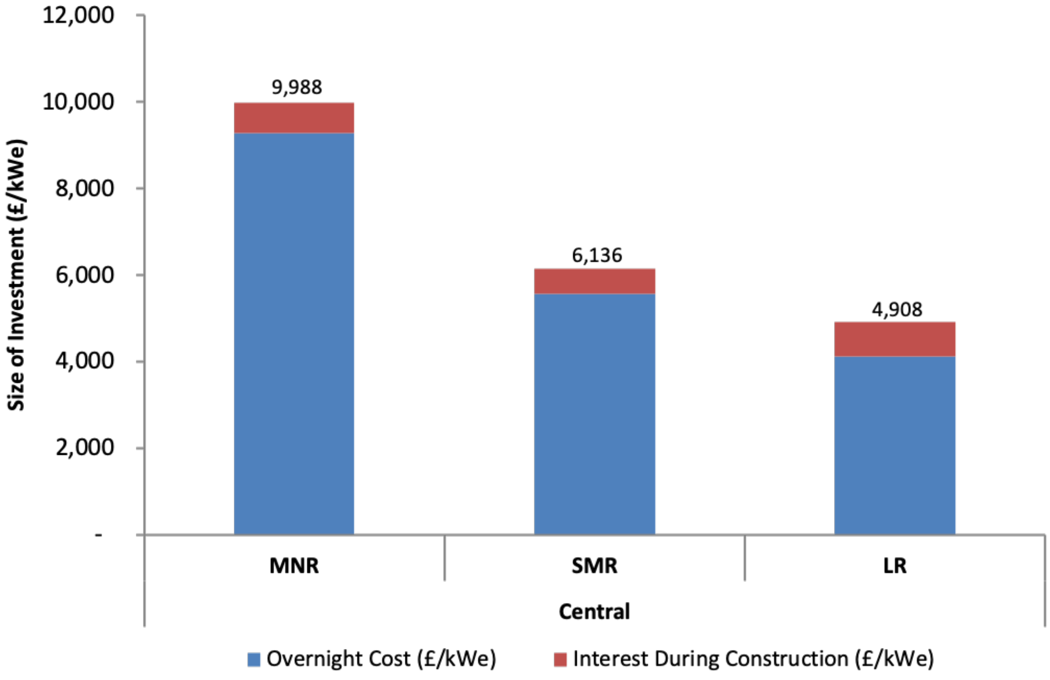

Figure 6.7: Central Size of Investment Estimates of NOAK-First On A Site MNRs, SMRs and Typical NOAK-First On A Site Large Scale Nuclear, considering a 5% compounded annual interest rate.

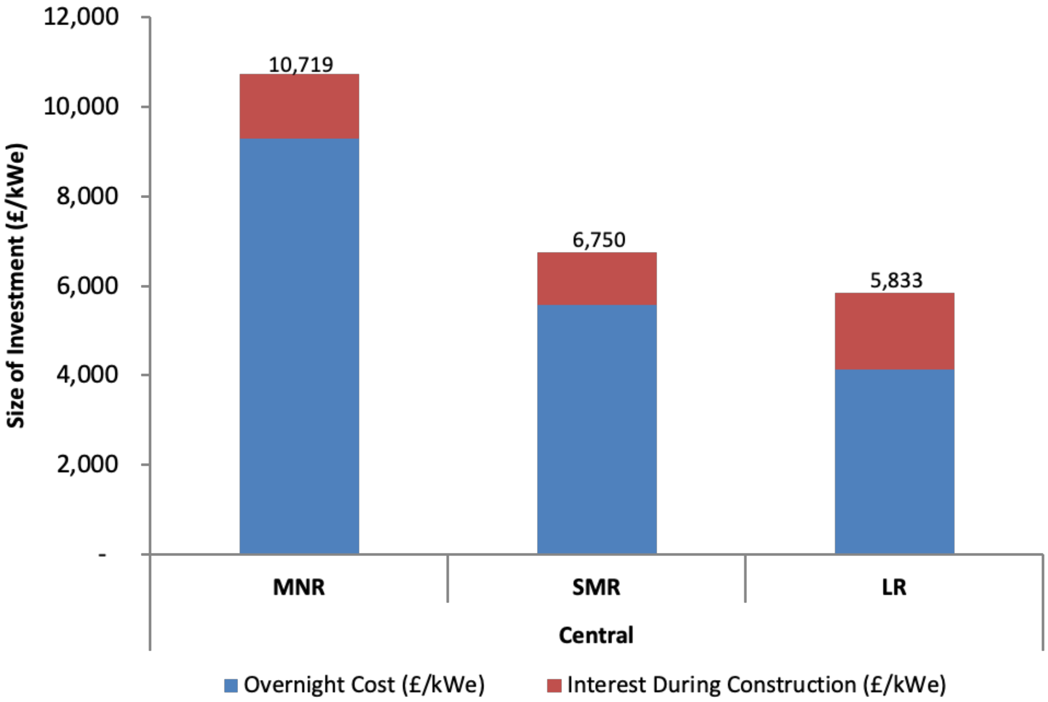

Figure 6.8: Central Size of Investment Estimates of NOAK-First On A Site MNRs, SMRs and Typical NOAK-First On A Site Large Scale Nuclear, considering a 10% compounded annual interest rate.

From Figures 6.7 and 6.8, the size of investment per unit capacity of NOAK-1st On A Site MNRs could be 59-63% greater than that of NOAK-1st On A Site SMRs and 84-104% greater than the size of investment per unit capacity of LRs. As expected, due to economies of scale, as one decreases the capacity of a nuclear system its capacity drops faster than its cost. However, as explained in Section 6.2, the speed at which the cost drops, as one decreases the capacity of a nuclear system, varies depending on the capacity range and the type of technology. All the previous implies that, in absolute terms (£), NOAK MNRs could represent a size of investment of the order of tens of millions, while NOAK SMRs might require an investment of the order of billions and large NOAK PWRs of the order of tens of billions[46].

6.4.1.2 Net Present Value (NPV)

As explained in Section 6.3, historical electricity prices paid by large non-domestic consumers are sufficiently similar to Hinkley Point C strike price to assume that MNR owners would save £104.39 for every MWh of electricity generated by MNRs. As a result, considering the previous assumption and the cash outflows detailed in Section 6.2, central NPV estimates of a NOAK-1st On A Site 4 MWe High Temperature Gas MNR were calculated based on a Discounted Cash Flow (DCF) analysis made for a

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[46] Figures rounded to the nearest 10 million or 10 billion, correspondingly.

60 years operational lifetime, 5-10% interest/discount rates, TRISO fuel compacts and a half core refuelling scheme. Results are presented below in Figure 6.9, for an open fuel cycle. Moreover, NOAK MNR figures are shown together with the central NPV estimates of NOAK SMRs and typical large PWRs assuming Hinkley Point C strike price (104.39 $\pounds/MWh$). As mentioned in Subsection 4.7.1, Hinkley Point C strike price is unlikely to be repeated in the foreseeable future. However, as indicated in Section 6.3, potential buyers of MNRs are already paying a price of electricity similar to Hinkley Point C strike price and, therefore, MNRs could operate at this price without any market intervention.

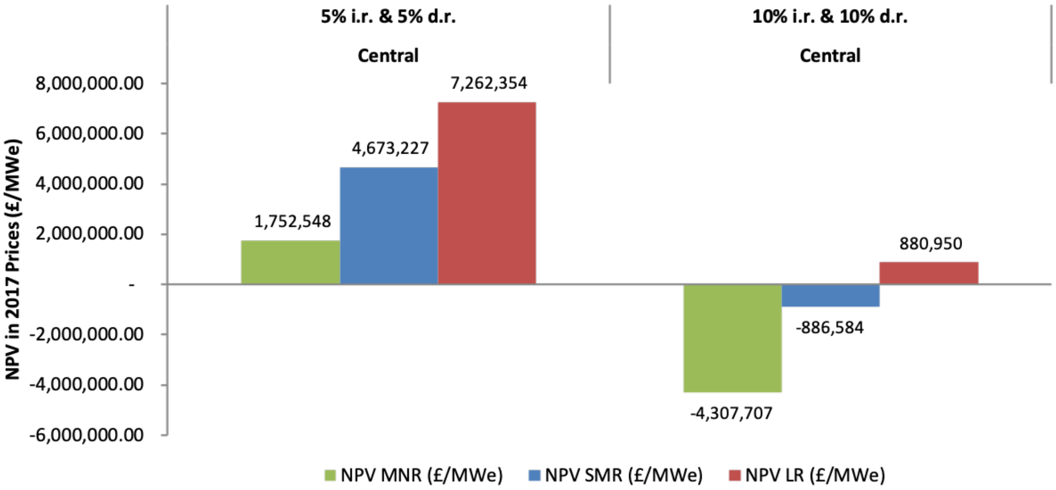

Figure 6.9: Central Net Present Value estimates of NOAK-First On A Site MNRs and Typical NOAK-First On A Site Large Scale Nuclear SMRs working on an open fuel cycle basis, considering 5-10% interest and discount rates.

From Figure 6.9, even considering high electricity prices, low interest/discount rates are fundamental in order to achieve positive NPVs, except for the case of large reactors. In addition, results suggest that NOAK MNRs are likely to have NPVs, in absolute terms (£), of the order of millions and possibly tens of millions while NOAK SMRs and large PWRs would have NPVs of the order of billions and tens of billions, respectively, under the same conditions[47].

6.4.1.3 Internal Rate of Return (IRR)

Following the same methodology used to calculate the IRR of near term SMRs (See Subsection 5.1.1.3), the IRR of a representative 4 MWe High Temperature Gas MNR, with a half core refuelling scheme, was estimated by plotting its NPV versus discount rate and identifying the zeros of the function. For consistency with the estimations shown in previous sections and in order to compare the results with those of SMRs

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[47] Figures rounded to the nearest 10 million or 10 billion, correspondingly.

and LRs, Hinkley Point C strike price was assumed (104.39 £/MWh), 0-10% interest rates were investigated and an open fuel cycle was considered. The finding, as shown below in Table 6.7, is that the smaller the reactor the more vulnerable it becomes to high discount rates. Moreover, in the case of micro nuclear reactors, it is clear that low interest rates might be fundamental to secure profits. Finally, Table 6.7 suggests that as the reactor capacity increases the annualised rate of return increases as well.

Table 6.7: IRR central estimates of near term NOAK-1st On A Site MNRs, SMRs and typical NOAK-1st On A Site Large Scale Nuclear assuming Hinkley Point C strike price, at different interest rates and in a UK context.

IRR central estimates of NOAK & 1st On A Site MNRs, SMRs and large scale PWRs.			
OPEN FUEL CYCLE			
Interest Rate (%)	**IRR MNR (%)**	**IRR SMR (%)**	**IRR LR (%)**
0	**6.5**	>**10**	>**10**
5	**6.5**	**9.5**	>**10**
10	**5.5**	**8.6**	>**10**

6.4.1.4 Return on Investment (ROI)

While [223] estimated a 7% ROI for a 20 $MWth$ U-battery, the results of this study indicate that the ROI of a 4 MWe MNR that resembles a 10 $MWth$ U-battery would be of around 6.26%. Assuming Hinkley Point C strike price (104.39 £/MWh) and confirming what their IRRs suggest, SMRs could have 52% higher ROIs than MNRs and LRs might offer more than twice the ROI of MNRs (See Figure 6.10).

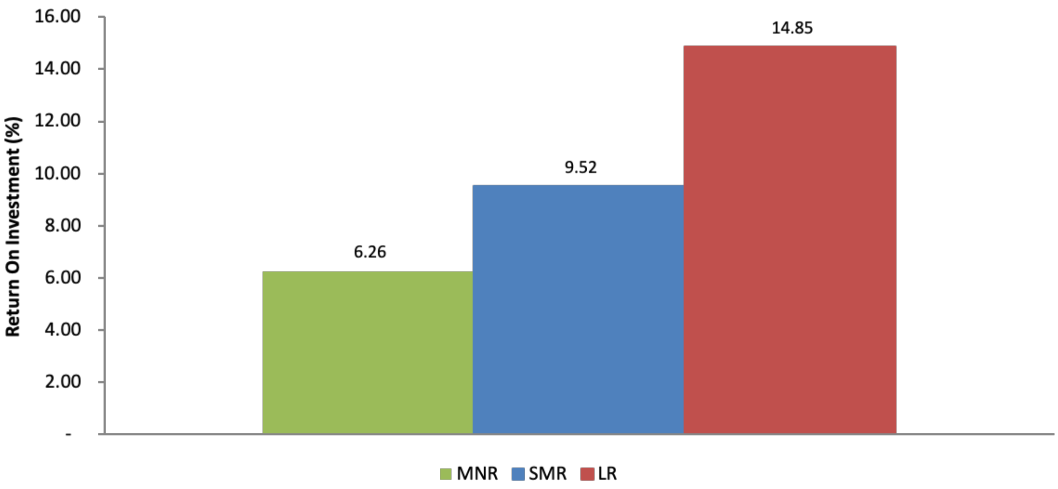

Figure 6.10: Central ROI estimates of NOAK & 1st On A Site MNRs, SMRs and typical large scale nuclear working on an open fuel cycle basis and assuming Hinkley Point C strike price.

6.4.1.5 Payback Period

In general, considering the results shown below and those presented in previous subsections, the pattern seems to be: the larger the capacity of the reactor, the larger its size of investment, the larger its annualised rate of return and, therefore, the shorter its payback period. From Figure 6.11, NOAK MNRs are likely to have payback periods of over 10 years, while the same financial figure might be of around 11 years for NOAK SMRs. In contrast, LRs should be capable of delivering payback periods below 10 years. Finally, considering that this study has been made assuming conservative cost reductions for the SMRs and for the MNRs, Figure 6.11 also implies that SMRs could achieve ≤10 years payback periods if further cost reductions are proven. Nonetheless, the same is not likely to happen in the case of MNRs even with further cost reductions.

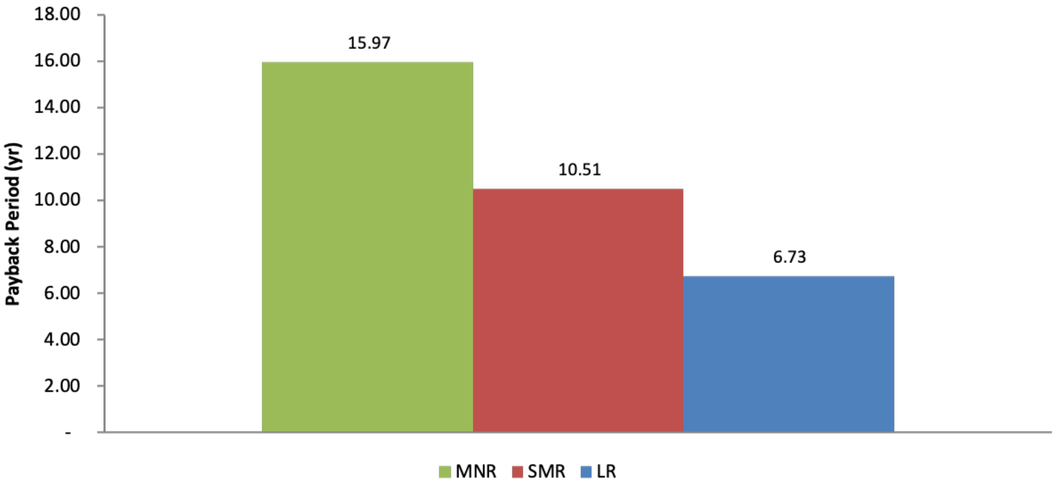

Figure 6.11: Central payback period estimates of NOAK & 1st On A Site MNRs, SMRs and typical large scale nuclear working on an open fuel cycle basis and assuming Hinkley Point C strike price.

6.4.1.6 Economic Dispatchability

In order to measure the weight of the capital cost component relative to the total levelised costs of near term MNRs the Economic Dispatchability (ED) of a representative NOAK 4 MWe High Temperature Gas MNR was estimated. The findings, as illustrated in Figure 6.12, suggest that while the absolute size of investment (£) is proportional to the size of the reactor, the weight of the capital cost component remains similar for SMRs and LRs, but increases for MNRs. Therefore, the economic drawback of not running a nuclear reactor at full power, during its available periods, could be 8%-30% higher for MNRs than for SMRs and LRs.

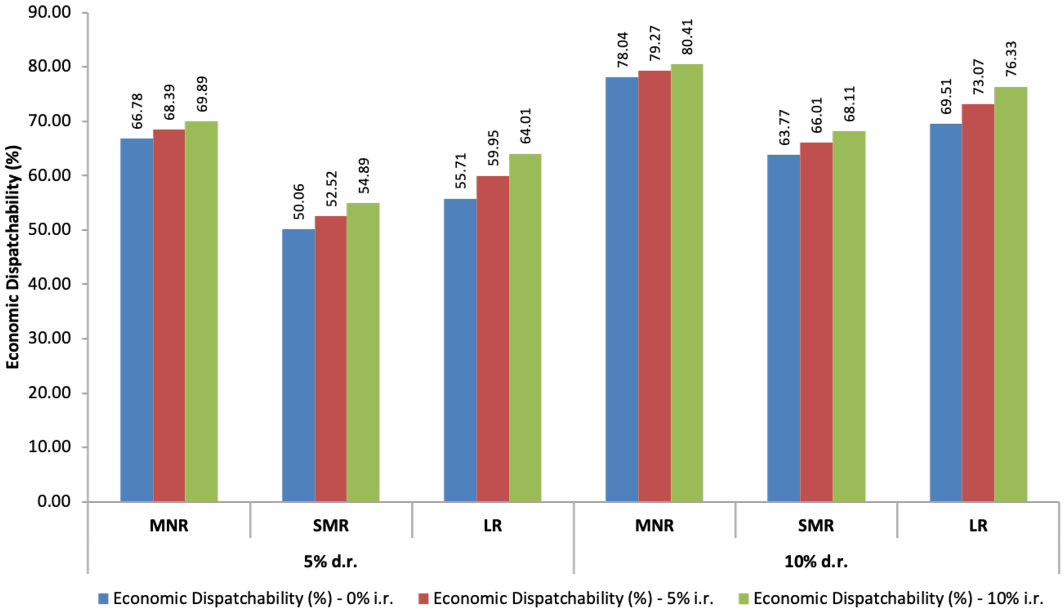

Figure 6.12: Central ED estimates of NOAK & 1st On A Site MNRs, SMRs and typical large scale nuclear working on an open fuel cycle basis.

6.4.2 Risk of Investment

6.4.2.1 Maturity of Technology

As noted in Subsection 5.1.2.1, at the time of this study, there are no licensed and commercially operational SMRs in the UK and, therefore, SMRs are not a mature technology. In relation, as a subcategory of SMRs, MNRs are not a mature technology either. In fact, the U-Battery which is resembled by the 4 MWe High Temperature Gas MNR here studied "is a concept which has been in development since 2008" [230]. Consequently, some financial risk is unavoidable for FOAK SMRs and MNRs.

6.4.2.2 Corruption Perception Index (CPI)

As a country-dependent indicator, in a UK context, this indicator would be no different than that presented in Subsection 5.1.2.2 for SMRs. This is, the risk of investment due to corruption would be very little for MNRs in the UK. While two-thirds of the 180 countries assessed in 2019 scored below 50, the UK scored a CPI of 77. In other words, according to the 2019 Transparency International's CPI, the UK is the world's 12th least corrupt country together with Canada, Australia and Austria [212].

6.4.2.3 Long-term Sovereign Credit Ratings (Foreign and Local Currency)

As mentioned in Subsection 5.1.2.3, with a 'AA/Stable' long-term foreign and local currency credit rating, the UK stands within the top 20 countries with the best credit ratings [214]. However, in order to be within the top 10, the UK has to provide more political and economic stability. On one hand, MNR design owners are targeting markets like the Canadian because of the high amount of remote communities and not because of the credit rating [224]. On the other hand, if the only criteria were the long-term sovereign credit ratings, with 'AAA/Stable' long-term foreign and local currency ratings Canada would still be a better candidate than the UK for MNR projects [214].

6.5 Techno-Economic Assessment

6.5.1 Affordability of Energy Services

6.5.1.1 Levelised Cost of Electricity (LCOE)

Utilising the estimated discounted cash flows of: 1) a 4 MWe High Temperature Gas MNR, 2) a 300 MWe Integral Pressurised Water SMR and 3) a 1200 MWe PWR the LCOE of near term MNRs, SMRs and typical large scale PWRs was estimated upon direct application of Equation B.1 (See appendix B.1). Moreover, a 60 years operational lifetime was assumed in all cases and 90%, 90% and 85% capacity factors were considered respectively. Similarly, the cases of 5-10% interest and discount rates were studied. Results are presented next.

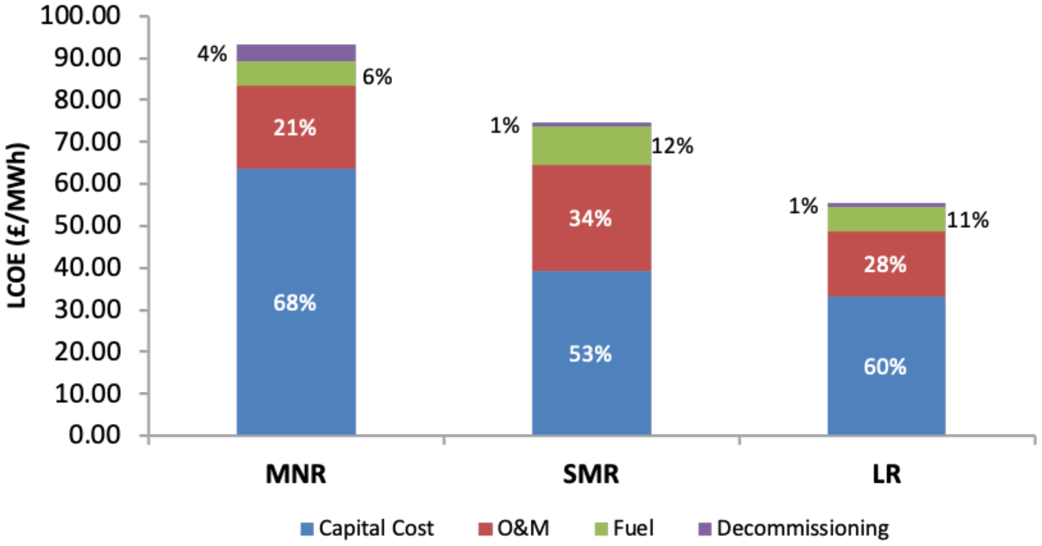

Figure 6.13: Central LCOE estimates of NOAK & 1st On A Site MNRs, SMRs and typical large scale PWRs working on an open fuel cycle basis, considering 5% interest and discount rates. *Be aware that MNR LCOEs compete in the retail electricity market while SMR and LR LCOEs compete in the wholesale electricity market.

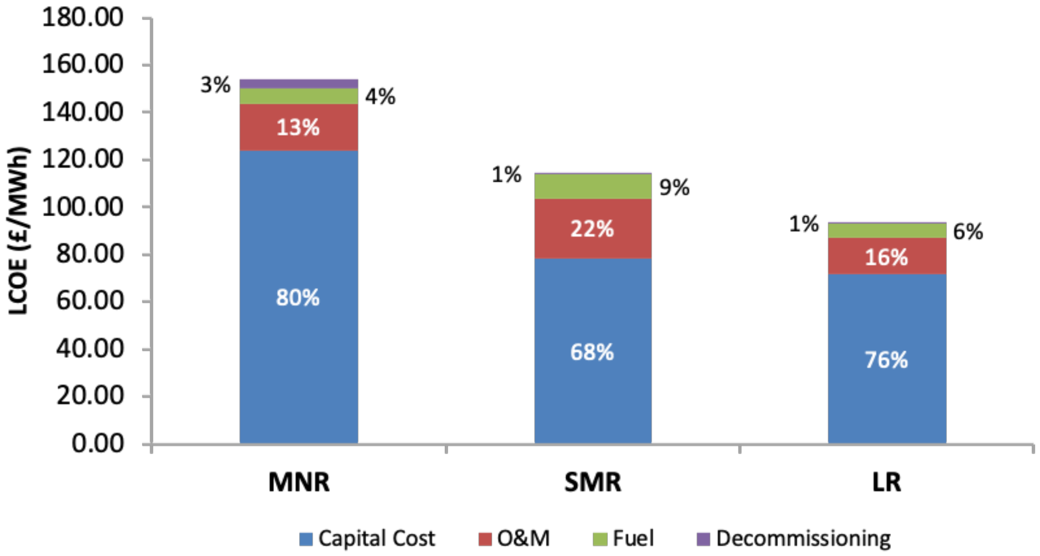

Figure 6.14: Central LCOE estimates of NOAK & 1st On A Site MNRs, SMRs and typical large scale PWRs working on an open fuel cycle basis, considering 10% interest and discount rates. *Be aware that MNR LCOEs compete in the retail electricity market while SMR and LR LCOEs compete in the wholesale electricity market.

From Figures 6.13 and 6.14, the LCOE of NOAK-1st On A Site MNRs, SMRs and typical large scale PWRs would be 93-154 £/MWh, 75-115 £/MWh and 55-94 £/MWh respectively. Furthermore, the affordability of energy services based on these results must be interpreted with care. On one hand, as discussed in Section 6.3, MNRs have been designed to satisfy the electricity needs of large non-domestic consumers who pay an average electricity price of around 104.41 £/MWh to electricity distributors in the retail electricity market. Consequently, if low interest/discount rates are achievable, MNRs would have strong chances of satisfying the electricity needs of large non-domestic consumers at an affordable price and, therefore, be an attractive investment option for non-electricity generation/distribution individual firms. On the other hand, SMRs and LRs compete in a market where their electricity generation costs have to be comparable with wholesale electricity market prices paid by electricity distributors to electricity generators (∼50 £/MWh), as they are likely to be owned by electricity generation companies and not by individual firms (See Section 4.7). As a result, single SMRs might have low chances of offering energy products and services at a competitive price, unless an external entity is willing to cover the difference between the LCOE of SMRs and wholesale electricity prices. Alternatively, if the electricity market keeps its fundamentals intact, the high LCOE of SMRs could only be less detrimental if SMRs are deployed in groups of ∼4 or where no other energy technologies are suitable (e.g. remote locations) or in situations where energy security comes with a premium.

6.5.1.2 Fuel Price Sensitivity Factor (FPSF)

While the fuel cost share of the LCOE is approximately 9-12% and 6-11% for SMRs and LRs respectively, the fuel cost of MNRs is likely to be responsible for only 4-6% of the LCOE of MNRs (See Figures 6.13 and 6.14 in Subsection 6.5.1). Consequently, as illustrated below in Figure 6.15, the impact of a doubling in fuel prices on the LCOE of MNRs could be significantly smaller than it would be on the LCOE of SMRs and LRs. This is a result of a higher contribution of capital and decommissioning costs towards the LCOE of MNRs and a lower contribution of O&M costs towards the same figure.

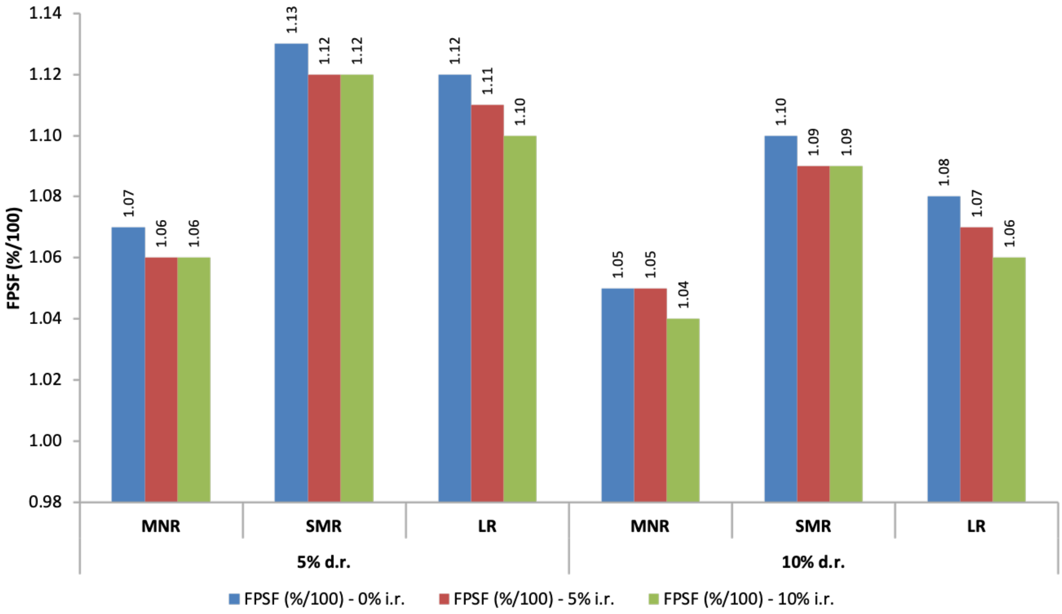

Figure 6.15: Central FPSF estimates of NOAK & 1st On A Site MNRs, SMRs and typical large scale PWRs working on an open fuel cycle basis.

6.5.2 Reliability and State of Technology

6.5.2.1 Capacity Factor

As mentioned at the beginning of Chapter 6, similar to the 2-4 years refuelling intervals of SMRs, most MNRs designs are targeting 2-5 years refuelling intervals [221, 222]. However, some MNR designs aiming for whole core refuelling schemes (e.g. [223]) intend to achieve up to 10 years refuelling intervals. As a result, it is recognised that some MNR technologies may offer less refuelling outages and, as a result, higher capacity factors than SMRs. Nevertheless, by convention, it is assumed that MNRs will have similar capacity factors to those of SMRs and a standard 90% capacity factor is normally used for MNR economic analyses [221, 225, 226, 228].

6.5.2.2 Availability Factor

Recalling Subsection 5.2.2.2, large nuclear reactors under development are aiming for availability factors of ≈95% [68]. Similarly, it is assumed that SMRs will achieve higher availability factors than large scale reactors (≥95%) [126, 168, 194]. In relation, MNR reactor design owners (e.g. [222, 228]) are targeting >90% availability factors. In fact, some economic analyses of advanced high temperature reactor systems [231] have found that, similar to SMRs, MNRs could achieve ≈95% availability factors.

6.5.2.3 Average Ramp Rate

Resembling SMR techno-economic assessments [168], MNR technical assessments [221] conclude that MNRs are expected to offer much greater rates of change of power output than large scale nuclear given that this technical feature is a consequence of smaller cores. In relation, as mentioned in Subsection 5.2.2.3, all new reactors must now be able to achieve average ramp rates of ≈5% of P_{max} per minute. In other words, while SMR design owners claim that their SMRs could achieve average ramp rates of 10% of P_{max} per minute, MNR studies assure that MNRs are likely to be better than SMRs [168, 221]. Nonetheless, in both cases, technical and market assessments of SMRs and MNRs assume conservative average ramp rates of 5% of P_{max} per minute [168, 225].

6.5.2.4 Average Response Time

Based on the limited publicly available information regarding the cycling parameters of MNRs, MNRs are expected to have similar average response times to those of SMRs and LRs. On one hand, as mentioned in Subsection 5.2.2.4, large scale reactors have typical average response times of 24 hours and SMRs are intended to achieve 24-36 hours cycling parameters [126, 168, 215]. On the other hand, reactor designs similar to the 4 MWe High Temperature Gas MNR here studied [232] suggest that MNRs may have average response times of around 20 hours. Consequently, in terms of average response times, MNRs are not likely to behave significantly different than SMRs and LRs.

6.5.2.5 Reserves-to-Production (R-P) Ratio

Given that the R-P ratio is calculated considering worldwide economically recoverable reserves and current production rates, of a given resource, the R-P ratio is no different for any uranium fuelled energy technology. In other words, MNRs, SMRs and LRs are equally vulnerable to physical interruptions of primary fuel supply. Moreover, according to the latest uranium resources and production figures [85], which are only published once every two years by the OECD Nuclear Energy Agency and the IAEA, the R-P ratio of conventional uranium is 149 years. In consequence, if 2019 uranium production rates remained constant and if no further conventional uranium economically recoverable reserves were identified, worldwide conventional uranium reserves would be enough to sustain 149 years of uranium demand.

6.6 Chapter Summary

Special Case: Micro Nuclear Reactors

- **Unique Contribution:** A full economic characterisation of near term MNRs was undertaken upon utilisation of an innovative cost escalation by parts approach (See Table 6.8 below).
    - Evidence suggests that economies of scale are weaker for HTGR-based MNRs in the ≤30 MWe range than for PWR-based SMRs in the ∼300 MWe range.

Table 6.8: Average Costs of Single NOAK MNRs and SMRs Relative to the Average Costs of Typical Large Scale PWRs.

Generating Cost	**Single MNRs Relative to LR**	**Single SMRs Relative to LR**
Capital Cost (£/MWe)	+84% to +104%	+16% to +25%
O&M Cost (£/MWe)	+35%	+75%
Fuel Cost (£/MWe)	+5% to +19%	+61% to +82%
Decommissioning Cost (£/MWe)	+436%	+11%
Total Cost (£/MWe)	+74% to +78%	+30% to +43%

- **Unique Contribution:** The attractiveness of investment and the techno-economic sustainability indicators of single MNRs were evaluated and compared with those of near term SMRs. Later on, results were presented relative to benchmark figures of large reactors (See Table 6.9 below).

  Attractiveness of Investment of near term MNRs

    - MNR technologies are not intended to compete in the wholesale electricity market. Their reduced size makes them suitable for large non-domestic firms intending to satisfy their own energy needs. With payback periods of around 16 years, MNRs may seem as an attractive investment compared to the grid if one considers the long operational lifetime expected for MNRs. However, the attractiveness of investment of MNRs can only be compared with that of small independent non-nuclear energy systems, but that comparison is beyond the scope of this study.
    - If MNRs were to participate in the same market as SMRs and large reactors, the investment required would be by far unjustifiable unless the size of investment (£) was a major limitation or if SMRs were unable to comply with the size restrictions of the desired location.

Table 6.9: Attractiveness of Investment and Techno-Economic Sustainability Central Estimates of Single MNRs and SMRs Relative to Single Large PWRs. Considerations: Open Fuel Cycle and Half Core Refuelling Scheme for MNRs, Open Fuel Cycle and 3-Batch Refuelling Scheme for SMRs, Hinkley Point C Strike Price, 10% interest rate and 5% discount rate.

Category	**Issue Addressed**	**Indicator**	**Single MNR vs. LR**	**Single SMR vs. LR**
Attractiveness of Investment	Financial Figures of Merit	Size of Investment (£/MWe)	+84%	+16%
		NPV (£/MWe)	-84%	-36%
		IRR	-45%	-14%
		ROI	-58%	-36%
		Payback Period	+137%	+56%
		Economic Dispatchability	+9%	-14%
	Risk of Investment	Maturity of Technology	Not Mature	Not Mature
		CPI	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Local Currency	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Foreign Currency	No Difference	No Difference
Techno-Economic	Affordability of Energy Services	LCOE	+59%	+27%
		FPSF	-3%	+2%
	Reliability and State of Technology	Capacity Factor	At Least +5 Percentage Points	Up to +10 Percentage Points
		Availability Factor	At Least +5 Percentage Points	Up to +10 Percentage Points
		Average Ramp Rate	≥0 Percentage Points	≥0 Percentage Points
		Average Response Time	No Difference	No Difference
		R-P Ratio	No Difference	No Difference

Techno-Economic Sustainability of near term MNRs

- Acknowledging that MNRs would compete in a retail market where the price of electricity is already similar to the estimated LCOE of MNRs, near term MNR technologies would be even more techno-economically sustainable than SMRs and LRs by extension. Although their capacity and availability factors might not be as high as those of SMRs, MNRs would be less exposed to primary fuel changes.

Chapter 7

MAIN FINDINGS & CONCLUSIONS

7.1 Single NOAK-1st On A Site SMR vs. NOAK LR

Considering the economic characterisation of near term SMRs derived in the present study, the attractiveness of investment and techno-economic sustainability of near term NOAK-First On A Site Integral Pressurised Water SMRs (∼300 MWe) was compared with that of large scale NOAK PWRs (∼1200 MWe), assuming an open fuel cycle, central fuel cycle costs and a 3-batch refuelling scheme. Furthermore, for this comparison, three scenarios were considered: 1) Typical UK central wholesale electricity market prices (48.77 £$/MWh$), 2) Wylfa Newydd strike price (89.39 £$/MWh$) and 3) Hinkley Point C strike price (104.39£$/MWh$). Similarly, for each scenario, two variants are presented: 1) Government owned utility in a regulated market and 2) private sector utility in a regulated market. On one hand, the government owned utility in a regulated market scenario was included in the tables presented below to illustrate how the negligible interest rates (<1%) and low discount rates (3-5%) only accessible to the government could significantly increase the competitiveness of SMRs with respect to private sector LRs. On the other hand, the UK central wholesale electricity market scenario was included in this section solely to illustrate how investments in nuclear technologies, of any kind, are not attractive under current market conditions and, therefore, why competitive strike prices must be agreed with the government if new investments in nuclear technologies are desired. Consequently, the analysis following the results presented below in Tables 7.1-7.3 focuses only on the Wylfa Newydd strike price and Hinkley Point C strike price scenarios and on the private sector variant.

Table 7.1: Attractiveness of Investment and Economic Sustainability of NOAK-1st On A Site SMRs vs. NOAK LRs in a Typical UK Central Wholesale Electricity Market Scenario.

ATTRACTIVENESS OF INVESTMENT - TYPICAL UK MARKET CONDITIONS						
Indicator	**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£/MWe)	5,561,542		6,749,858		5,832,525	
Net Present Value (NPV) (£/MWe)	-2,573,136	-3,468,271	-4,656,588	-5,694,741	-1,894,241	-3,660,087
Internal Rate of Return (IRR) (%)	0.4		Net Loss		2.5	
Return on Investment (ROI) (%)	1.63				4.81	
Payback Period (yr)	61.32				20.81	
Economic Dispatchability (ED) (%)	41.10	50.06	54.89	68.11	64.01	76.33
Maturity of Technology	Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77					
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable					
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable					

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Table 7.1 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - TYPICAL UK MARKET CONDITIONS						
Indicator	**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	60.21	70.90	78.48	114.65	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.15	1.13	1.12	1.09	1.10	1.06
Capacity Factor (%)	90 - 95				85 - 90	
Availability Factor (%)	>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant$5				5	
Average Response Time (h)	24 - 36				~24	
Reserves-to-Production (R-P) Ratio (yr)	149					

Table 7.2: Attractiveness of Investment and Economic Sustainability of NOAK-1st On A Site SMRs vs. LRs in a UK Scenario Assuming Wylfa Newydd Strike Price.

ATTRACTIVENESS OF INVESTMENT - WYLFA NEWYDD STRIKE PRICE						
Indicator	**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£/MWe)	5,561,542		6,749,858		5,832,525	
Net Present Value (NPV) (£/MWe)	6,556,869	2,897,644	1,709,328	-2,183,172	4,118,013	-343,605
Internal Rate of Return (IRR) (%)	8.5		6.5		9.5	
Return on Investment (ROI) (%)	7.39				12.14	
Payback Period (yr)	13.53				8.24	
Economic Dispatchability (ED) (%)	41.10	50.06	54.89	68.11	64.01	76.33
Maturity of Technology	Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77					
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable					
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable					

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Table 7.2 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - WYLFA NEWYDD STRIKE PRICE						
Indicator	**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	60.21	70.90	78.48	114.65	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.15	1.13	1.12	1.09	1.10	1.06
Capacity Factor (%)	90 - 95				85 - 90	
Availability Factor (%)	>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant$5				5	
Average Response Time (h)	24 - 36				~24	
Reserves-to-Production (R-P) Ratio (yr)	149					

Table 7.3: Attractiveness of Investment and Economic Sustainability of NOAK-1st On A Site SMRs vs. NOAK LRs in a UK Scenario Assuming Hinkley Point C Strike Price.

ATTRACTIVENESS OF INVESTMENT - HINKLEY POINT C STRIKE PRICE						
Indicator	**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£/MWe)	5,561,542		6,749,858		5,832,525	
Net Present Value (NPV) (£/MWe)	9,927,968	5,248,151	4,059,835	-886,584	6,337,936	880,950
Internal Rate of Return (IRR) (%)	>10		8.6		>10	
Return on Investment (ROI) (%)	9.52				14.85	
Payback Period (yr)	10.51				6.73	
Economic Dispatchability (ED) (%)	41.10	50.06	54.89	68.11	64.01	76.33
Maturity of Technology	Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77					
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable					
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable					

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Table 7.3 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - HINKLEY POINT C STRIKE PRICE						
Indicator	**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	60.21	70.90	78.48	114.65	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.15	1.13	1.12	1.09	1.10	1.06
Capacity Factor (%)	90 - 95				85 - 90	
Availability Factor (%)	>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant$5				5	
Average Response Time (h)	24 - 36				~24	
Reserves-to-Production (R-P) Ratio (yr)	149					

While undiscounted figures suggest that near term SMRs and LRs could have similar economic performances on a per MWe basis, discounted figures show a clear dominance of LRs over SMRs in economic terms. Undiscounted figures of merit indicate that near term SMRs might have a Return on Investment (ROI) 35-40% smaller than that of similar LRs, 7.4-9.5% and 12.1-14.9% respectively. Similarly, the results presented above imply that the payback period of SMRs and LRs could be of approximately 11-14 years and 7-9 years, accordingly. In contrast, discounted figures suggest that with an Internal Rate of Return (IRR) of 9.5 to >10%, LRs could be much better suited than SMRs with IRR=6.5-8.6% for the typical 5-10% discount rate applicable to private utilities in a regulated market.

With an Economic Dispatchability (ED) of 54.89-68.11%, the capital cost component of the total levelised cost of NOAK SMRs is marginally smaller than that of NOAK LRs (64.01-76.33%). As a result, near term SMRs might be slightly better suited for load-following energy generation schedules than LRs, although it would not be economically convenient for either. Furthermore, considering the typical 10% interest rate applied to the private sector, SMRs are likely to have a size of investment per unit capacity (£/MWe) 16% higher than that of equivalent LRs. In other words, if the only criterion was the absolute size of investment (£) then SMRs would naturally have a clear advantage over LRs due to their lower capacity. However, if a given market actor could afford any of the two options, then LRs could be a more attractive option due to their smaller size of investment per unit capacity.

As a result of higher capacity factors, near term SMRs could have better cash inflows per MWe than LRs. Nonetheless, the Operation and Maintenance (O&M) cost of near term SMRs might be heavily affected by economies of scale. Similarly, the fuel cost of SMRs (£/MWe) could be significantly higher than that of equivalent LRs, most likely due to a poorer neutron economy which could result in higher uranium inventories per MWe and the requirement of a higher uranium enrichment grade. Consequently, considering the private sector utility in a regulated market scenario, NOAK LRs might have a Net Present Value (NPV), on a per MWe basis, equivalent to 1.5-2.5 times the NPV of near term SMRs.

Regarding the affordability of energy services, the situation is no different. With a Levelised Cost of Electricity (LCOE) around 20% smaller than that of NOAK SMRs (78.48-114.65 £/MWh), NOAK LRs could offer more competitive energy prices (61.56-93.60 £/MWh). In addition, the Fuel Price Sensitivity Factor (FPSF) of SMRs (1.09-

1.12) indicates that the LCOE of SMRs would be more affected by fuel price variations than the LCOE of LRs with a FPSF of around 1.06-1.10. Nevertheless, in contrast with the attractiveness of investment and the affordability of energy services evaluations, near term SMRs could achieve slightly better reliability and state of technology figures than typical large scale reactors. Although both SMRs and LRs would be limited by the same R-P Ratio (∼149 years) and similar average response times (∼24 hours), NOAK SMRs promise higher capacity factors (90-95%), higher availability factors (>95%) and higher average ramp rates ($\geqslant$5 % of P_{max}/min) than NOAK LRs.

At the time of this study, single near term SMRs do not seem sufficiently attractive to justify investments in them unless the only criterion was the size of investment in absolute terms (£) or the suitability for remote locations. Not only better financial figures of merit are foreseen for NOAK LRs, but also SMRs would be a riskier investment given that they would be a less mature technology. Nonetheless, although single SMRs would not be able to offer more affordable energy services than LRs, energy prices could be comparable. In addition, SMRs are likely to display technological properties that would strengthen local/regional energy security and contribute towards a smoother operation of electrical grids. In conclusion, single SMRs may be slightly more techno-economically sustainable than their large scale equivalents. However, if single SMRs are to be available, further development is required to attract market actors towards SMR investments.

7.1.1 Single SMRs - Further Cost Reductions Scenario

Firstly, while single SMRs could be slightly more techno-economically sustainable, results suggest that near term single SMRs are unlikely to compete with the attractiveness of investment of typical large scale reactors unless further cost reductions are demonstrated. Secondly, as mentioned in Subsection 4.2.4.3, the results presented throughout this study are subject to change due to the potential impact of the ‘factory-built factor’ which is yet to be validated. Recalling Subsection 5.3.1, single SMRs could offer the same and perhaps a slightly better financial performance than typical large scale reactors if a 32% overnight cost reduction due to construction in a factory environment was demonstrated. In other words, if single SMRs are to come to the market, a significant overnight cost reduction (∼32%) due to the ‘factory-built factor’ must be validated in order to reverse the economies of scale effect.

7.2 Multiple (4) SMRs vs. Single LR

In Chapter 4 the Test Case: Multiple (4) SMRs vs. Single LRs was presented for each of the estimated cost components of near term SMRs. Now, in Tables 7.4-7.6 the attractiveness of investment and the techno-economic sustainability of 4 Integral Pressurised Water SMRs (cumulative capacity of ∼1200 MWe) is presented and compared with the attractiveness of investment and the techno-economic sustainability of large scale nuclear reactors (∼1200 MWe). Similarly, it was assumed that the construction schedule of SMRs would be such that the first year of construction of any subsequent SMR would coincide with the second year of construction of the previous SMR. This was assumed to take advantage of the time value of money. Furthermore, just as in the case of the single SMR analysis previously presented in Section 7.1, the UK central wholesale electricity market scenario was included in the tables presented below to show how regardless of the scale or configuration of nuclear reactors, nuclear technologies are not an attractive investment under central wholesale electricity market conditions. Similarly, the government owned utility in a regulated market variant was included in this section only to illustrate how the attractiveness of investment and techno-economic sustainability of multiple SMRs improves significantly with low interest and discount rates. Consequently, the analysis of Tables 7.4-7.6 was made considering only the Wylfa Newydd strike price scenario, the Hinkley Point C strike price scenario and the private sector utility in a regulated market variant.

Table 7.4: Attractiveness of Investment and Economic Sustainability of Multiple NOAK SMRs vs. Single NOAK LRs in a Typical UK Central Wholesale Electricity Market Scenario.

ATTRACTIVENESS OF INVESTMENT - TYPICAL UK MARKET CONDITIONS						
Indicator	**1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs**				**Single NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£/MWe)	4,935,868		5,254,468		5,832,525	
Net Present Value (NPV) (£/MWe)	-1,458,090	-2,573,259	-2,891,859	-4,126,750	-1,894,241	-3,660,087
Internal Rate of Return (IRR) (%)	0.5		0.5		2.5	
Return on Investment (ROI) (%)	2.30				4.81	
Payback Period (yr)	43.42				20.81	
Economic Dispatchability (ED) (%)	41.31	50.96	52.52	67.35	64.01	76.33
Maturity of Technology	Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77					
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable					
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable					

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Table 7.4 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - TYPICAL UK MARKET CONDITIONS						
Indicator	**1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs**				**Single NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	55.54	66.41	68.59	103.53	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.16	1.14	1.13	1.10	1.10	1.06
Capacity Factor (%)	90 - 95				85 - 90	
Availability Factor (%)	>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant$5				5	
Average Response Time (h)	24 - 36				∼24	
Reserves-to-Production (R-P) Ratio (yr)	149					

Table 7.5: Attractiveness of Investment and Economic Sustainability of Multiple NOAK SMRs vs. Single LRs in a UK Scenario Assuming Wylfa Newydd Strike Price.

ATTRACTIVENESS OF INVESTMENT - WYLFA NEWYDD STRIKE PRICE						
Indicator	**1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs**				**Single NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£/MWe)	4,935,868		5,254,468		5,832,525	
Net Present Value (NPV) (£/MWe)	7,280,719	3,352,212	3,033,612	-1,065,669	4,118,013	-343,605
Internal Rate of Return (IRR) (%)	8.5		7.5		9.5	
Return on Investment (ROI) (%)	8.79				12.14	
Payback Period (yr)	11.37				8.24	
Economic Dispatchability (ED) (%)	41.31	50.96	52.52	67.35	64.01	76.33
Maturity of Technology	Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77					
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable					
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable					

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Table 7.5 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - WYLFA NEWYDD STRIKE PRICE						
Indicator	**1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs**				**Single NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	55.54	66.41	68.59	103.53	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.16	1.14	1.13	1.10	1.10	1.06
Capacity Factor (%)	90 - 95				85 - 90	
Availability Factor (%)	>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant$5				5	
Average Response Time (h)	24 - 36				~24	
Reserves-to-Production (R-P) Ratio (yr)	149					

Table 7.6: Attractiveness of Investment and Economic Sustainability of Multiple NOAK SMRs vs. Single NOAK LRs in a UK Scenario Assuming Hinkley Point C Strike Price.

ATTRACTIVENESS OF INVESTMENT - HINKLEY POINT C STRIKE PRICE						
Indicator	**1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs**				**Single NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£/MWe)	4,935,868		5,254,468		5,832,525	
Net Present Value (NPV) (£/MWe)	10,507,377	5,540,092	5,221,492	64,583	6,337,936	880,950
Internal Rate of Return (IRR) (%)	>10		9.5		>10	
Return on Investment (ROI) (%)	11.19				14.85	
Payback Period (yr)	8.94				6.73	
Economic Dispatchability (ED) (%)	41.31	50.96	52.52	67.35	64.01	76.33
Maturity of Technology	Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77					
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable					
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable					

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Table 7.6 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - HINKLEY POINT C STRIKE PRICE						
Indicator	**1 NOAK-1st On A Site + 3 NOAK-Nth On A Site SMRs**				**Single NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	55.54	66.41	68.59	103.53	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.16	1.14	1.13	1.10	1.10	1.06
Capacity Factor (%)	90 - 95				85 - 90	
Availability Factor (%)	>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant 5$				5	
Average Response Time (h)	24 - 36				~24	
Reserves-to-Production (R-P) Ratio (yr)	149					

In contrast with the case of single SMRs, undiscounted and discounted figures of merit suggest that multiple SMRs have strong chances of achieving similar economic performances to those of large scale reactors. Neglecting the time value of money, multiple SMRs might be able to offer payback periods of around 9-12 years while LRs with an equivalent capacity could have payback periods of 7-9 years. In other words, undiscounted financial figures of merit indicate that multiple SMRs may have a Return on Investment (ROI) 25-28% smaller than single large scale reactors, 8.8-11.2% and 12.1-14.9% respectively. Similarly, with internal rates of return of 7.5-9.5% and 9.5 to >10% accordingly, discounted financial figures of merit show that both, multiple SMRs and single LRs, have relatively the same suitability for typical private sector interest and discount rates.

Although it is smaller than that of single SMRs, the Economic Dispatchability (ED) of multiple SMRs is still similar to that of equivalent large reactors, 52.52-67.35% and 64.01-76.33% respectively. This means that the capital cost component of multiple SMRs and large reactors accounts for more than half of their corresponding LCOEs. Nonetheless, contrary to single SMRs, multiple SMRs require a lower average investment ($£/MWe$) than that needed for large reactors. Considering private sector utilities in a regulated market, the size of investment of multiple SMRs has been estimated to be almost 10% smaller than that required for large reactors with the same capacity. Nonetheless, the NPV of large reactors would still be 20-35% larger than the NPV of multiple SMRs. This has been attributed to the fact that having multiple SMRs instead of a single one could result in reduced sizes of investment and decommissioning costs. However, O&M and fuel costs do not decrease sufficiently to have an LCOE smaller than that of large reactors.

On one hand, regarding the affordability of energy products and services, large reactors are likely to have a slightly smaller LCOE than multiple SMRs, 61.56-93.60 $£/MWh$ and 68.59-103.53 $£/MWh$ respectively. Nevertheless, this improvement of the LCOE compared to that of single SMRs would be at the expense of a moderately higher Fuel Price Sensitivity Factor (FPSF). In other words, multiple SMRs would be more susceptible to electricity price increments due to fuel price variations than LRs, even more than single SMRs. On the other hand, the reliability and modernity of energy services (e.g. capacity factor, availability factor, average ramp rate, etc.) of multiple SMRs would be identical to the reliability and modernity of energy services provided by single SMRs.

Considering all the previous, from an investor's point of view, investing in not mature technologies such as multiple SMRs might be worth the risk in exchange of a deferred payment schedule, an overall smaller size of investment and similar financial figures of merit to those of mature LRs. From the consumer point of view, the relatively small extra cost of multiple SMRs instead of a single LR could be justified by slightly higher capacity factors, availability factors and average ramp rates. In other words, single or multiple SMRs are prone to have better techno-economic sustainability features than large scale reactors, but only multiple SMRs have chances of competing with large reactors in terms of attractiveness of investment. Similarly, multiple SMR configurations could create redundancy in terms of electricity generation and, as a result, enhanced energy security. Therefore, if the SMR technology is to exist and provide more techno-economically sustainable energy systems than large reactors, it is much more likely to be in the form of multiple SMRs rather than single SMRs.

7.2.1 Multiple SMRs - Further Cost Reductions Scenario

As previously discussed in Subsection 7.1.1, single SMRs could be slightly more techno-economically sustainable, but will need a significant overnight cost reduction (∼32%) due the ‘factory-built factor’ to be demonstrated in order to compete with the attractiveness of investment of large scale nuclear. In contrast, results suggest that multiple SMRs might be more techno-economically sustainable and are likely to achieve similar financial performances to those of typical large scale reactors even if no further cost reductions are demonstrated. Consequently, as shown in Subsection 5.3.1, the attractiveness of investment of single SMRs could be comparable to that of large reactors and multiple SMRs could be more cost-efficient than large scale nuclear if a 32% overnight cost reduction due to construction in a factory environment was validated. In other words, only considering the cost reductions assumed throughout this study multiple SMRs could be as financially competitive as large reactors and, therefore, any further cost reduction like the ‘factory-built factor’ would only make multiple SMRs more attractive than large scale nuclear.

7.3 NOAK MNRs vs. NOAK SMRs vs. NOAK LRs

As shown below in Tables 7.7-7.8, which summarise the results previously presented in Sections 6.4-6.5 and illustrate how to utilise the results provided in this study to assess particular cases; if single MNRs, SMRs and LRs are assumed to compete in the same market in a UK context (e.g. energy producers selling to energy distributors at wholesale market prices) a clear pattern was identified: the size or capacity of a given nuclear reactor is directly proportional to its absolute size of investment (£), NPV, IRR, ROI and, as a result, inversely proportional to its payback period. Furthermore, while the long-term sovereign credit ratings and the corruption perception index would be the same for any technology in this case, the economic dispatchability of SMRs is the best followed by those of LRs and MNRs which are comparable. In consequence, if the size of investment (£) and suitability for remote locations are not a limitation and if multiple reactor configurations are not considered, the mature large reactor technology is by far the most attractive investment out of the three reactor technologies followed by single SMRs and lastly by MNRs.

Contrary to the attractiveness of investment, results suggest that the techno-economic sustainability of nuclear reactors is inversely proportional to the size of a given nuclear reactor. On one hand, energy services provided by large scale reactors are likely to be more affordable than energy services provided by small and micro reactor technologies due to a lower LCOE. However, MNR energy services are the least exposed to changes in primary fuel prices. On the other hand, small and micro reactor technologies offer more reliable energy services than LRs due to higher capacity factors, higher availability factors, higher ramp rates and similar response times that promote the smooth operation of electrical grids. Consequently, results suggest that MNRs might have the best techo-economic sustainability features followed by SMRs and lastly by LRs. Nevertheless, the conclusions presented in this and the previous paragraph are just a cross technology comparison exercise because in reality these three nuclear energy technologies are very unlikely to compete in the same markets.

SMRs are likely to be owned by electricity generators and utilised to contribute towards the satisfaction of domestic energy needs and, as a result, compete in the same market that LRs. Consequently, if the size of investment (£) and location are not a limitation, SMRs could only compete with LRs in the form of multiple SMRs with a cumulative capacity comparable to that of large reactors. Alternatively, single SMRs would be able to compete with LRs only if no other baseload technology was suitable for the intended location or if the size of investment was a limitation. In any case, both nuclear energy technologies require a form of market intervention (e.g. competitive strike prices) because without these both technologies are unviable regardless of the potential techno-economic benefits of SMRs.

In contrast with SMRs and LRs, MNRs are prone to be owned by large non-domestic individual firms in order to satisfy their own energy demand and, as a result, to compete with energy services provided by energy distributors at non-domestic retail prices. Moreover, contrary to SMRs and LRs, MNRs are not likely to require any form of market intervention as their LCOE is inclined to be comparable with energy prices already paid by large non-domestic consumers. Therefore, MNRs not only could offer large non-domestic energy consumers an attractive investment project and the chance to stop relying on the grid (if a connection to the grid was available), but also MNRs aim to provide around 6% annualised rates of return and, in consequence, profits after 16 years of operation. Nevertheless, mature MNRs will not necessarily be more techno-economically sustainable than the grid in countries like the UK with well developed grid infrastructures. Although MNRs intend to achieve competitive techno-economic figures, the grid is arguably more modern and reliable due to its diversified energy mix. Lastly, in locations where no connection to the grid was available, the attractiveness of investing in MNRs and their techno-economic sustainability could only be compared with that of other independent small energy systems (e.g. small fossil fuelled energy systems) which could cope with the large uninterrupted non-domestic energy demands in question. However, that comparison is beyond the scope of this study.

In conclusion, based only in the results here presented, MNRs are a more attractive investment than SMRs and LRs, each in their respective markets, as MNRs require little or no market intervention to be profitable. However, if competitive strike prices are available, then SMRs and LRs are a more attractive investment than MNRs. In contrast, regardless of the scenario assessed, the techno-economic sustainability of nuclear reactor technologies was found to be inversely proportional to the size or capacity of the nuclear energy technology. Therefore, MNRs are inclined to have the best techno-economic sustainability figures, followed by SMRs and lastly by LRs. Similarly, it is acknowledged that the techno-economic sustainability of MNRs compared to that of the grid, depends upon the maturity and modernity of the corresponding electrical grid infrastructure. Consequently, in a UK scenario, MNRs have strong chances of being an attractive investment, but they will not necessarily be more techno-economically sustainable than the grid. Alternatively, in remote locations where a connection to the grid was unavailable or unviable, the attractiveness of investment and the techno-economic sustainability of MNRs compared to that of other independent small energy systems requires further investigation.

Table 7.7: Attractiveness of Investment and Economic Sustainability of Single NOAK-1st On A Site MNRs vs. Single NOAK-1st On A Site SMRs vs. NOAK LRs in a UK Scenario Assuming Hinkley Point C Strike Price.

ATTRACTIVENESS OF INVESTMENT - HINKLEY POINT C STRIKE PRICE										
Indicator	**NOAK-1st On A Site MNRs**				**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Government Funded <1% i.r.**		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**3% d.r.**	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£/MWe)	9,280,560		10,719,046		5,561,542		6,749,858		5,832,525	
Net Present Value (NPV) (£/MWe)	7,549,040	2,460,191	1,021,704	-4,307,707	9,927,968	5,248,151	4,059,835	-886,584	6,337,936	880,950
Internal Rate of Return (IRR) (%)	6.5		5.5		>10		8.6		>10	
Return on Investment (ROI) (%)	6.26				9.52				14.85	
Payback Period (yr)	15.97				10.51				6.73	
Economic Dispatchability (ED) (%)	58.33	66.78	69.89	80.41	41.10	50.06	54.89	68.11	64.01	76.33
Maturity of Technology	Not Mature				Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77									
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable									
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable									

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Table 7.7 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - HINKLEY POINT C STRIKE PRICE										
Indicator	**NOAK-1st On A Site MNRs**				**NOAK-1st On A Site SMRs**				**NOAK LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Government Funded <1% i.r.**		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**3% d.r.**	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	70.80	88.69	97.87	154.23	60.21	70.90	78.48	114.65	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.08	1.07	1.06	1.04	1.15	1.13	1.12	1.09	1.10	1.06
Capacity Factor (%)	$\geqslant$90				90 - 95				85 - 90	
Availability Factor (%)	$\geqslant$90				>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant$5				$\geqslant$5				5	
Average Response Time (h)	∼24				24 - 36				∼24	
Reserves-to-Production (R-P) Ratio (yr)	149									

Table 7.8: Attractiveness of Investment and Economic Sustainability of Single NOAK-1st On A Site 4 MWe MNRs vs. Single NOAK-1st On A Site 300 MWe SMRs vs. NOAK 1200 MWe LRs in a UK Scenario Assuming Hinkley Point C Strike Price.

ATTRACTIVENESS OF INVESTMENT - HINKLEY POINT C STRIKE PRICE										
Indicator	**NOAK-1st On A Site 4 MWe MNRs**				**NOAK-1st On A Site 300 MWe SMRs**				**NOAK 1200 MWe LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Government Funded <1% i.r.**		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**3% d.r.**	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Size of Investment (£)	37,122,238		42,876,185		1,668,462,553		2,024,957,385		6,999,030,437	
Net Present Value (NPV) (£)	30,196,160	9,840,763	4,086,816	-17,230,826	2,978,390,433	1,574,445,306	1,217,950,473	-265,975,191	7,605,522,605	1,057,140,170
Internal Rate of Return (IRR) (%)	6.5		5.5		>10		8.6		>10	
Return on Investment (ROI) (%)	6.26				9.52				14.85	
Payback Period (yr)	15.97				10.51				6.73	
Economic Dispatchability (ED) (%)	58.33	66.78	69.89	80.41	41.10	50.06	54.89	68.11	64.01	76.33
Maturity of Technology	Not Mature				Not Mature				Mature	
Corruption Perception Index (CPI) (0-100)	77									
Long-Term Sovereign Credit Rating, Local Currency	AA/Stable									
Long-Term Sovereign Credit Rating, Foreign Currency	AA/Stable									

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Table 7.8 – Continued from previous page.

TECHNO-ECONOMIC INDICATORS - HINKLEY POINT C STRIKE PRICE										
Indicator	**NOAK-1st On A Site 4 MWe MNRs**				**NOAK-1st On A Site 300 MWe SMRs**				**NOAK 1200 MWe LRs**	
	Government Funded <1% i.r.		**Private Sector 10% i.r.**		**Government Funded <1% i.r.**		**Private Sector 10% i.r.**		**Private Sector 10% i.r.**	
	3% d.r.	**5% d.r.**	**5% d.r.**	**10% d.r.**	**3% d.r.**	**5% d.r.**	**5% d.r.**	**10% d.r.**	**5% d.r.**	**10% d.r.**
Levelised Cost of Electricity (LCOE) (£/MWh)	70.80	88.69	97.87	154.23	60.21	70.90	78.48	114.65	61.56	93.60
Fuel Price Sensitivity Factor (FPSF) (%/100)	1.08	1.07	1.06	1.04	1.15	1.13	1.12	1.09	1.10	1.06
Capacity Factor (%)	$\geqslant$90				90 - 95				85 - 90	
Availability Factor (%)	$\geqslant$90				>95				85 - 95	
Average Ramp Rate (% of P_{max}/min)	$\geqslant$5				$\geqslant$5				5	
Average Response Time (h)	~24				24 - 36				~24	
Reserves-to-Production (R-P) Ratio (yr)	149									

7.4 Chapter Summary

Main Findings & Conclusions

- **Unique Contribution:** Following the corresponding economic characterisations presented earlier in this study (See Table 7.9 below for a summary), an innovative set of attractiveness of investment and techno-economic sustainability indicators were evaluated for single NOAK MNRs, single NOAK SMRs and multiple (4) NOAK SMRs in a UK scenario. Similarly, in order to facilitate cross-technology comparison, results were presented relative to the corresponding figures of benchmark large reactors (See Table 7.10 below). As a result, the following conclusions were made:

  Attractiveness of Investment

  - The attractiveness of investment of nuclear energy technologies, in a UK scenario, was found to be directly proportional to the corresponding reactor capacity. The larger the reactor, the smaller the average size of investment (£/MWe), the larger the average NPV (£/MWe), the higher the IRR, the higher the ROI, and the shorter the payback period. In order to reverse this 'Large is Best' conclusion and tilt the economics decidedly in favour of SMRs a 32% overnight cost reduction due to construction in a factory environment would have to be demonstrated.
  - If MNRs, SMRs and LRs were to compete in the same market, and if the size of investment (£) and location-size-specific characteristics **were not a limitation**, then LRs would be the most attractive investment followed by multiple SMRs, single SMRs and lastly by MNRs.
  - If MNRs, SMRs and LRs were to compete in the same market, and if the size of investment (£) and location-size-specific characteristics **were a limitation**, then MNRs would be the most attractive investment followed by single SMRs, multiple SMRs and lastly by LRs.
  - **Note:** In reality, nuclear energy technologies could be more attractive than it has been suggested in this study if a CO_2 tax is introduced. Similarly, MNRs will compete in a different market and, therefore, their addition to this analysis was only for illustrative purposes. The attractiveness of investment of MNRs can only be compared against other small independent energy

supply systems designed to satisfy the energy demand of large non-domestic firms. However, this comparison is beyond the scope of this study.

Techno-Economic Sustainability

- In contrast with the attractiveness of investment, the techno-economic sustainability of nuclear energy systems was found to be inversely proportional to the capacity of the corresponding nuclear reactor. Although the affordability of energy services is affected as the size of a nuclear energy system is reduced, this is compensated by a more modern and reliable grid.
- On one hand, acknowledging that MNRs would compete in a market where the price of electricity is already similar to the LCOE foreseen for MNRs, MNRs are likely to be the most techno-economically sustainable nuclear energy system. On the other hand, the techno-economical sustainability of MNRs relative to other non-nuclear energy technologies competing in the same market requires further investigation.
- Limiting the analysis to the wholesale electricity market, if location-size-specific characteristics **were not a limitation**, then multiple SMRs would be the most techno-economically sustainable configuration followed by single SMRs and lastly by LRs. This would be a result of the fact that, while single or multiple SMR configurations would have similar modernity and reliability levels, multiple SMRs would be able to offer more affordable energy prices than single SMRs.
- Limiting the analysis to the wholesale electricity market, if location-size-specific characteristics **were a limitation**, then single SMRs would be the most techno-economically sustainable configuration followed by multiple SMRs and lastly by LRs.

Table 7.9: Average Costs of Single NOAK MNRs, Single NOAK SMRs, and Multiple (4) NOAK SMRs Relative to the Average Costs of Typical Large Scale PWRs.

Generating Cost	**Single MNRs Relative to LR**	**Single SMRs Relative to LR**	**Multiple (4) SMRs Relative to LR**
Capital Cost (£/MWe)	+84% to +104%	+16% to +25%	-10% to +4%
O&M Cost (£/MWe)	+35%	+75%	+36% to +45%
Fuel Cost (£/MWe)	+5% to +19%	+61% to +82%	+51% to +59%
Decommissioning Cost (£/MWe)	+436%	+11%	-14% to -8%
Total Cost (£/MWe)	+74% to +78%	+30% to +43%	+2% to +20%

Table 7.10: Attractiveness of Investment and Techno-Economic Sustainability Central Estimates of Single NOAK MNRs, and Single and Multiple (4) NOAK SMRs Relative to Single Large PWRs. Considerations: Open Fuel Cycle and Half Core Refuelling Scheme for MNRs, Open Fuel Cycle and 3-Batch Refuelling Scheme for SMRs, 10% interest rate and 5% discount rate.

Category	**Issue Addressed**	**Indicator**	**Single MNR vs. LR**	**Single SMR vs. LR**	**4 SMRs vs. LR**
Attractiveness of Investment	Financial Figures of Merit	Size of Investment (£/MWe)	+84%	+16%	-10%
		NPV (£/MWe)	-84%	-58% to -36%	-26% to -18%
		IRR	-45%	-32% to -14%	-21% to -5%
		ROI	-58%	-39% to -36%	-28% to -25%
		Payback Period	+137%	+56% to +64%	+33% to +38%
		Economic Dispatchability	+9%	-14%	-18%
	Risk of Investment	Maturity of Technology	Not Mature	Not Mature	Not Mature
		CPI	No Difference	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Local Currency	No Difference	No Difference	No Difference
		Long-Term Sovereign Credit Rating, Foreign Currency	No Difference	No Difference	No Difference

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Table 7.10 – Continued from previous page.

Category	**Issue Addressed**	**Indicator**	**Single MNR vs. LR**	**Single SMR vs. LR**	**4 SMRs vs. LR**
Techno-Economic	Affordability of Energy Services	LCOE	+59%	+27%	+11%
		FPSF	-3%	+2%	+4%
	Reliability and State of Technology	Capacity Factor	At Least +5 Percentage Points	Up to +10 Percentage Points	Up to +10 Percentage Points
		Availability Factor	At Least +5 Percentage Points	Up to +10 Percentage Points	Up to +10 Percentage Points
		Average Ramp Rate	≥0 Percentage Points	≥0 Percentage Points	≥0 Percentage Points
		Average Response Time	No Difference	No Difference	No Difference
		R-P Ratio	No Difference	No Difference	No Difference

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Appendix A

Attractiveness of Investment Indicators: Evaluation Methods

A.1 Size of Investment

$$SINV = P \sum_{t=t_{c_i}}^{t_{c_f}} ONT_t \times (1+r)^{t_{c_f}-t+1} \tag{A.1}$$

Where:

- $SINV$: Size of Investment needed for a power plant up to commissioning (£).
- P: Electrical capacity of the power plant (MWe).
- t_{c_i}: Starting year of the power plant construction period (e.g. 2018).
- t_{c_f}: Final year of the power plant construction period (e.g. 2023) - Previous year to power plant start-up.
- ONT_t: Approximated funds (a fraction of the overnight capital cost) to be invested in year t, per unit of final installed capacity (£/MWe). The overnight capital cost is assumed to include: construction, contingency and owner costs (e.g. licensing). In other words, "the cost of the construction of a power plant if no interest was accrued during construction, as if the project was completed 'overnight' "[68].
- r: Reference interest rate, for the period of interest (%/100).

Source: simplified version of that presented in [68]. The calculation method proposed by [68] can lead to the false conclusion that no interest is paid for the last construction year, and, therefore the limits of the summation presented in Equation A.1 differ from those presented in [68].

A.2 Net Present Value

$$NPV = \sum_{t=t_{start}}^{t_{end}} \frac{P_t \times 8760 \times Cf_t}{(1+r)^{t-t_0}} \times R_t - \sum_{t=t_{start}}^{t_{end}} \frac{K_t + O\&M_t + F_t + C_t + D_t}{(1+r)^{t-t_0}} \quad \text{(A.2)}$$

Where:

- NPV: Net Present Value of an energy supply technology (£).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).
- R_t: Reference selling price of electricity in year t (£/kWh).
- r: Reference interest or discount rate, accordingly (%/100).
- t_0: A point in time (a particular year) to which all costs and benefits are discounted. Typically assumed to coincide with the start of operations.
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- K_t: Capital expenditures in the year t (£).
- $O\&M_t$: Operation and Maintenance costs in the year t (£).
- F_t: Fuel expenditures in the year t (£).
- C_t: Carbon expenditures (carbon taxes) in the year t (£).
- D_t: Decommissioning and waste management costs in the year t (£).

Source: [68].

A.3 Internal Rate of Return

$$NPV = \sum_{t=t_{start}}^{t_{end}} \frac{P_t \times 8760 \times Cf_t}{(1+IRR)^{t-t_0}} \times R_t - \sum_{t=t_{start}}^{t_{end}} \frac{K_t + O\&M_t + F_t + C_t + D_t}{(1+IRR)^{t-t_0}} = 0 \quad \text{(A.3)}$$

Where:

- NPV: Net Present Value of an energy supply technology (£).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).
- R_t: Reference selling price of electricity in year t (£/kWh).
- IRR: Internal Rate of Return (%/100).
- t_0: A point in time (a particular year) to which all costs and benefits are discounted. Typically assumed to coincide with the start of operations.
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- K_t: Capital expenditures in the year t (£).
- $O\&M_t$: Operation and Maintenance costs in the year t (£).
- F_t: Fuel expenditures in the year t (£).
- C_t: Carbon expenditures (carbon taxes) in the year t (£).
- D_t: Decommissioning and waste management costs in the year t (£).

Source: [68].

A.4 Return on Investment

$$ROI = \frac{(R - OM - F - C - D)}{ONT} \times (T \times Cf) \tag{A.4}$$

Where:

- ROI: Return on Investment of an energy supply technology (%/100).
- R: Reference price of electricity for the period considered (£/kWh).
- OM: Undiscounted operation and maintenance costs per unit of electricity generated (£/kWh).
- F: Undiscounted fuel expenditures per unit of electricity generated (£/kWh).

- C: Undiscounted carbon expenditures (carbon taxes) per unit of electricity generated (£/kWh).

- D: Undiscounted decommissioning and waste management costs per unit of electricity generated (£/kWh).

- ONT: Overnight capital cost per unit of final installed capacity (£/kWe). The overnight capital cost is assumed to include the present value of: construction, contingency and owner costs (e.g. licensing).

- Cf: Reference capacity factor, of the power plant in question, for the period considered (%/100).

- T: Time period for which the ROI is calculated, usually a year (h).

Source: simplified version of that presented in [68].

A.5 Payback Period

$$PP = \frac{ONT}{(R - OM - F - C - D) \times (8760 \times Cf)} \tag{A.5}$$

Where:

- PP: Payback Period of an energy supply technology (yr).

- ONT: Overnight capital cost per unit of final installed capacity (£/kWe). The overnight capital cost is assumed to include undiscounted: construction, contingency and owner costs (e.g. licensing).

- R: Reference price of electricity for the period considered (£/kWh).

- OM: Undiscounted operation and maintenance costs per unit of electricity generated (£/kWh).

- F: Undiscounted fuel expenditures per unit of electricity generated (£/kWh).

- C: Undiscounted carbon expenditures (carbon taxes) per unit of electricity generated (£/kWh).

- D: Undiscounted decommissioning and waste management costs per unit of electricity generated (£/kWh).

- Cf: Reference capacity factor, of the power plant in question, for the period considered (%/100).

- 8760: Total number of hours in a year (h).

Source: inferred from [68].

A.6 Economic Dispatchability

$$ED = \frac{\overline{K_t}}{LCOE} \tag{A.6}$$

Where:

$$\overline{K_t} = \frac{\sum_{t=t_{start}}^{t_{end}} \frac{K_t}{(1+r)^{t-t_0}}}{\sum_{t=t_{start}}^{t_{end}} \frac{P_t \times 8760 \times Cf_t}{(1+r)^{t-t_0}}} \tag{A.7}$$

$$LCOE = \frac{\sum_{t=t_{start}}^{t_{end}} \frac{K_t + O\&M_t + F_t + C_t + D_t}{(1+r)^{t-t_0}}}{\sum_{t=t_{start}}^{t_{end}} \frac{P_t \times 8760 \times Cf_t}{(1+r)^{t-t_0}}} \tag{A.8}$$

- ED: Economic Dispatchability of an energy supply technology (%/100).
- K_t: Capital expenditures in the year t (£).
- $O\&M_t$: Operation and Maintenance costs in the year t (£).
- F_t: Fuel expenditures in the year t (£).
- C_t: Carbon expenditures (carbon taxes) in the year t (£).
- D_t: Decommissioning and waste management costs in the year t (£).
- r: Reference interest or discount rate, accordingly (%/100).
- t_0: A point in time (a particular year) to which all costs are discounted. Typically assumed to coincide with the start of operations.
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: personal interpretation of the version presented in [64].

A.7 Maturity of Technology

Table A.1: Maturity of Technology Criteria

Scenario	Category	Interpretation
Country attempting to deploy a specific type of energy supply technology/power plant for the first time.	'mature'	Similar power plants have already been licensed and operated, in the country of origin. Therefore, the technology is mature.
	'not mature'	Similar power plants have not been licensed and operated, in the country of origin. Therefore, the technology is not mature.
Country attempting to deploy a specific type of energy supply technology/power plant not for the first time.	'mature'	Similar power plants have already been licensed and operated, in the country of interest. Therefore, the technology is mature.
	'not mature'	Similar power plants have not been licensed and operated, in the country of interest. Therefore, the technology is not mature.

A.8 Long-Term Sovereign Credit Ratings

Table A.2: Standard & Poor's Credit Rating Categories [73, 75].

Category	**Bond's Credit Quality Rating**	**Interpretation**
AAA	Investment Grade	Extremely strong capacity to meet financial commitments.
AA	Investment Grade	Very strong capacity to meet financial commitments.
A	Investment Grade	Strong capacity to meet financial commitments.
BBB	Investment Grade	Adequate capacity to meet financial commitments.
BB	Speculative Grade	Less vulnerable in the near-term, but faces major ongoing uncertainties to adverse business, financial and economic conditions.
B	Speculative Grade	More vulnerable to adverse business, financial and economic conditions, but currently has the capacity to meet financial commitments.
CCC	Speculative Grade	Currently vulnerable and dependent on favourable business, financial and economic conditions to meet financial commitments.
CC	Speculative Grade	Highly vulnerable; default has not yet occurred, but is expected to be a virtual certainty.
C	Speculative Grade	Currently highly vulnerable to non-payment, and ultimate recovery is expected to be lower than that of higher rated obligations.
R	Speculative Grade	Under regulatory supervision.
SD or D	Speculative Grade	An obligor rated 'SD' (Selective Default) or 'D' is in default on one or more of its financial obligations.
NR	Not rated	Not rated.

The ratings from 'AA' to 'CCC' may be modified by the addition of a plus (+) or minus (−) sign to show relative standing within the major rating categories [75].

Appendix B

Techno-Economic Indicators: Evaluation Methods

B.1 Levelised Cost of Electricity

$$
\begin{aligned}
LCOE &= \frac{\sum_{t=t_{start}}^{t_{end}} \frac{K_t+O\&M_t+F_t+C_t+D_t}{(1+r)^{t-t_0}}}{\sum_{t=t_{start}}^{t_{end}} \frac{E_t}{(1+r)^{t-t_0}}} \times 10^{-2} \\
&= \frac{\sum_{t=t_{start}}^{t_{end}} \frac{K_t+O\&M_t+F_t+C_t+D_t}{(1+r)^{t-t_0}}}{\sum_{t=t_{start}}^{t_{end}} \frac{P_t\times 8760\times Cf_t}{(1+r)^{t-t_0}}} \times 10^{-2}
\end{aligned}
\tag{B.1}
$$

Where:

- $LCOE$: Levelised Cost of Electricity (p/kWh).
- K_t: Capital expenditures in the year t (£).
- $O\&M_t$: Operation and Maintenance costs in the year t (£).
- F_t: Fuel expenditures in the year t (£).
- C_t: Carbon expenditures (carbon taxes) in the year t (£).
- D_t: Decommissioning and waste management costs in the year t (£).
- E_t: Net energy/electricity produced, by the power plant in question, in the year t (kWh).
- r: Reference interest or discount rate, accordingly (%/100).
- t_0: A point in time (a particular year) to which all costs are discounted. Typically assumed to coincide with the start of operations.

- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: [64, 68, 78, 80]

B.2 Fuel Price Sensitivity Factor

$$FPSF = 1 + \frac{\overline{F_t}}{LCOE} \tag{B.2}$$

Where:

$$\overline{F_t} = \frac{\sum_{t=t_{start}}^{t_{end}} \frac{F_t}{(1+r)^{t-t_0}}}{\sum_{t=t_{start}}^{t_{end}} \frac{P_t \times 8760 \times Cf_t}{(1+r)^{t-t_0}}} \tag{B.3}$$

$$LCOE = \frac{\sum_{t=t_{start}}^{t_{end}} \frac{K_t + O\&M_t + F_t + C_t + D_t}{(1+r)^{t-t_0}}}{\sum_{t=t_{start}}^{t_{end}} \frac{P_t \times 8760 \times Cf_t}{(1+r)^{t-t_0}}} \tag{B.4}$$

- $FPSF$: Fuel Price Sensitivity Factor of an energy supply technology (%/100).
- K_t: Capital expenditures in the year t (£).
- $O\&M_t$: Operation and Maintenance costs in the year t (£).
- F_t: Fuel expenditures in the year t (£).
- C_t: Carbon expenditures (carbon taxes) in the year t (£).
- D_t: Decommissioning and waste management costs in the year t (£).
- r: Reference interest or discount rate, accordingly (%/100).
- t_0: A point in time (a particular year) to which all costs are discounted. Typically assumed to coincide with the start of operations.
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).

- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: [64, 66, 67, 68, 78, 80]

B.3 Capacity Factor

$$C_f = \frac{NAG}{NMPG} \times 100 = \frac{NAG}{NMC \times PH} \times 100 \tag{B.5}$$

Where:

- C_f: Net Capacity Factor of an energy supply technology (%).
- NAG: Net actual generation, of the power plant in question, during the time period considered (MWh).
- $NMPG$: Net maximum possible generation, of the power plant in question, during the time period considered (MWh).
- NMC: Net maximum capacity of the power plant (MWe).
- PH: Period hours or number of hours, within the time period considered, that the power plant was in active state (h). This is, the addition of the number of hours that the power plant was active-available (generation or in reserve mode) and active-unavailable (failures, testing, work being performed, or an adverse condition).

Source: [82].

B.4 Availability Factor

$$A_f = \frac{AH}{PH} \times 100 \tag{B.6}$$

Where:

- A_f: Availability Factor of an energy supply technology (%).
- AH: Available Hours or the number of hours, within the time period considered, that the energy supply unit was capable of generating, regardless of whether it was actually in service or in reserve mode (h).

- PH: Period hours or number of hours, within the time period considered, that the power plant was in active state (h). This is, the addition of the number of hours that the power plant was active-available (generation or in reserve mode) and active-unavailable (failures, testing, work being performed, or an adverse condition).

Source: [82].

B.5 Average Ramp Rate

$$ARR = \frac{RUR + RDR}{2} \tag{B.7}$$

Where:

- ARR: Average Ramp Rate of an energy supply technology (% of P_{max}/min).
- RUR: Ramp-up rate (% of P_{max}/min). See Equation B.8 in Appendix B.5.1.
- RDR: Ramp-down rate (% of P_{max}/min). See Equation B.9 in Appendix B.5.2.

B.5.1 Ramp-up Rate

$$RUR = \frac{RUR_{max}}{P_{max}} \times 100 \tag{B.8}$$

Where:

- RUR: Ramp-up rate of an energy supply technology (% of P_{max} $/min$).
- RUR_{max}: Maximum rate of power increase (MWe/min).
- P_{max}: Maximum (aka nominal) output power (MWe).

Source: modified version of that proposed by [64].

B.5.2 Ramp-down Rate

$$RDR = \frac{RDR_{max}}{P_{max}} \times 100 \tag{B.9}$$

Where:

- RUR: Ramp-down rate of an energy supply technology (% of P_{max} $/min$).
- RDR_{max}: Maximum rate of power decrease (MWe/min).
- P_{max}: Maximum (aka nominal) output power (MWe).

Source: modified version of that proposed by [64].

B.6 Average Response Time

$$ART = \frac{MUT + MDT}{2} \tag{B.10}$$

Where:

- ART: Average Response Time of an energy supply technology (min).
- MUT: Minimum up time or minimum time for which a unit must operate before being shut down (min) [64].
- MDT: Minimum down time or minimum time for which a unit must remain shut before returning to power (min) [64].

B.7 Reserves-to-Production Ratio

$$RP\ Ratio = \frac{R}{P} \tag{B.11}$$

Where:

- $RP\ Ratio$: Reserves-to-Production Ratio (yr).
- R: Economically recoverable reserves of a given resource (t or m^3, accordingly).
- P: Annual production rate of the resource in question ((t/yr) or (m^3/yr), accordingly).

Source: [64, 84].

Appendix C

Environmental Sustainability Indicators: Evaluation Methods

C.1 Global Warming Potential

$$GWP_{Tot} = \sum_{j}^{J} GWP_j \times B_j \tag{C.1}$$

Where:

- GWP_{Tot}: Total global warming potential of an energy supply technology (kg CO_2 equiv/kWh).
- GWP_j: GWP factor of green house gas j (kg CO_2 equiv/kg). See CML-IA database [89] for a comprehensive list of GWP factors.
- B_j: Emission of GHG j (kg/kWh).
- J: Total number of GHGs emitted.

Source: [64].

C.2 Ozone Depletion Potential

$$ODP_{Tot} = \sum_{j}^{J} ODP_j \times B_j \tag{C.2}$$

Where:

- ODP_{Tot}: Total ozone depletion potential of an energy supply technology (kg $CFC-11$ equiv/kWh).

- ODP_j: ODP factor of ozone depleting gas j ($kg\ CFC-11$ equiv/kg). See CML-IA database [89] for a comprehensive list of ODP factors.
- B_j: Emission of ozone depleting gas j (kg/kWh).
- J: Total number of ozone depleting substances emitted.

Source: [64].

C.3 Photochemical Ozone Creation Potential

$$POCP_{Tot} = \sum_{j}^{J} POCP_j \times B_j \tag{C.3}$$

Where:

- $POCP_{Tot}$: Total photochemical ozone creation potential of an energy supply technology ($kg\ C_2H_4$ equiv/kWh).
- $POCP_j$: POCP factor of ozone precursor j ($kg\ C_2H_4$ equiv/kg). See CML-IA database [89] for a comprehensive list of POCP factors.
- B_j: Emission of ozone precursor j (kg/kWh).
- J: Total number of ozone precursors emitted.

Source: [64].

C.4 Freshwater Eco-Toxicity Potential

$$FWETP_{Tot} = \sum_{j}^{J} FWETP_j \times B_j \tag{C.4}$$

Where:

- $FWETP_{Tot}$: Total freshwater eco-toxicity potential of an energy supply technology (kg 1,4-DCB equiv/kWh).
- $FWETP_j$: FWETP factor of substance j (kg 1,4-DCB equiv/kg). See CML-IA database [89] for a comprehensive list of FWETP factors.
- B_j: Emission of substance j (kg/kWh).
- J: Total number of toxic species released to freshwater.

Source: [64].

C.5 Marine Eco-Toxicity Potential

$$METP_{Tot} = \sum_{j}^{J} METP_j \times B_j \tag{C.5}$$

Where:

- $METP_{Tot}$: Total marine eco-toxicity potential of an energy supply technology (kg 1,4-DCB equiv/kWh).
- $METP_j$: METP factor of substance j (kg 1,4-DCB equiv/kg). See CML-IA database [89] for a comprehensive list of METP factors.
- B_j: Emission of substance j (kg/kWh).
- J: Total number of toxic species released to seawater.

Source: [64].

C.6 Acidification Potential

$$AP_{Tot} = \sum_{j}^{J} AP_j \times B_j \tag{C.6}$$

Where:

- AP_{Tot}: Total acidification potential of an energy supply technology (kg SO_2 equiv/kWh).
- AP_j: AP factor of acid gas j (kg SO_2 equiv/kg). See CML-IA database [89] for a comprehensive list of AP factors.
- B_j: Emission of acid gas j (kg/kWh).
- J: Total number of acid gases emitted.

Source: [64].

C.7 Eutrophication Potential

$$EP_{Tot} = \sum_{j}^{J} \sum_{m}^{M} EP_j \times B_{jm} \tag{C.7}$$

Where:

- EP_{Tot}: Total eutrophication potential of an energy supply technology ($kg\ PO_4^{3-}$ equiv/kWh).
- EP_j: Generic EP factor of nutrient j emitted to air, water or soil ($kg\ PO_4^{3-}$ equiv/kg). See CML-IA database [89] for a comprehensive list of EP factors.
- B_{jm}: Emission of nutrient j to medium m (kg/kWh).
- J: Total number of nutrients emitted.
- M: Total number of emission mediums considered for the assessment (e.g. air, freshwater, seawater, agricultural soil and industrial soil or simply air, water and soil).

Source: [64, 88].

C.8 Land Occupation

$$ILU = \frac{TLA \times (t_{start} - t_{end})}{\sum_{t=t_{start}}^{t_{end}} P_t \times 8760 \times Cf_t} \tag{C.8}$$

- ILU: Total impact of on land use over time of an energy supply technology (m^2yr/kWh).
- TLA: Total land area occupied (m^2).
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: inferred from [64].

C.9 Greenfield Land Use

$$GF = \frac{GFA}{TLA} \times 100 \tag{C.9}$$

- GF: Greenfield land used for the construction of a new build power plant, relative to the total land area occupied (%).

- GFA: Greenfield field land area transformed (m^2).
- TLA: Total land area occupied (m^2).

Source: [64].

C.10 Terrestrial Eco-Toxicity Potential

$$TETP_{Tot} = \sum_{j}^{J} TETP_j \times B_j \tag{C.10}$$

Where:

- $TETP_{Tot}$: Total terrestrial eco-toxicity potential of an energy supply technology (kg 1,4-DCB equiv/kWh).
- $TETP_j$: TETP factor of substance j (kg 1,4-DCB equiv/kg). See CML-IA database [89] for a comprehensive list of TETP factors.
- B_j: Emission of substance j (kg/kWh).
- J: Total number of toxic species released to land.

Source: [64].

C.11 Non-Radioactive Waste

$$NRW = \frac{\sum_{j}^{J} w_j}{\sum_{t=t_{start}}^{t_{end}} P_t \times 8760 \times Cf_t} \tag{C.11}$$

- NRW: Total non-radiactive waste mass produced by an energy supply technology (kg/kWh).
- w_j: Non-radioactive waste mass produced in life cycle stage j (kg).
- J: Total number of life cycle stages.
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: inferred from [67].

C.12 Radioactive Waste

$$RW = \frac{\sum_j^J w_j}{\sum_{t=t_{start}}^{t_{end}} P_t \times 8760 \times Cf_t} \tag{C.12}$$

- RW: Total volume of radioactive waste produced by an energy supply technology (m^3/kWh).
- w_j: Volume of radioactive waste produced in life cycle stage j (m^3).
- J: Total number of life cycle stages.
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: modified version of that proposed by [64].

C.13 Usage of Non-Renewable Non-Energetic Resources

$$ADP_{Tot} = \sum_j^J ADP_j \times B_j \tag{C.13}$$

Where:

- ADP_{Tot}: Total abiotic resource depletion potential of an energy supply technology ($kg\ Sb$ equiv/kWh).
- ADP_j: ADP factor of mineral j ($kg\ Sb$ equiv/kg). See CML-IA database [89] for a comprehensive list of ADP factors.
- B_j: Consumption of mineral j (kg/kWh).
- J: Total number of minerals (non-renewable non-energetic resources) consumed.

Source: inferred from [64].

Appendix D

Social Sustainability Indicators: Evaluation Methods

D.1 Flexibility

$$Flex = Og + Ic + Tri + H \tag{D.1}$$

Where:

- $Flex$: Total flexibility of an energy supply technology (0 - 40 points).
- Og: Suitability of an energy supply technology for off-grid applications or small grids (10 if the criterion is fulfilled, 0 otherwise).
- Ic: Ability of an energy supply technology to increase production capacity (10 if the criterion is fulfilled, 0 otherwise).
- Tri: Suitability of an energy supply technology for trigeneration (10 if the criterion is fulfilled, 0 otherwise).
- H: Ability of an energy supply technology to produce hydrogen via thermal/thermochemical processes (10 if the criterion is fulfilled, 0 otherwise).

Source: modified version of the flexibility index proposed by [64].

D.2 Total Employment

$$TE = \frac{\sum_{j}^{J} DE_j \times T_j + IE_j \times T_j}{\sum_{t=t_{start}}^{t_{end}} P_t \times 8760 \times Cf_t} \tag{D.2}$$

- TE: Total employment provision over the entire life cycle of an energy supply technology ($person - yr/TWh$).
- DE_j: Direct employment provision in life cycle stage j (no. of people employed).
- IE_j: Indirect employment provision in life cycle stage j (no. of people employed).
- T_j: Duration of employment in life cycle stage j (yr).
- J: Total number of life cycle stages.
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: inferred from [64].

D.3 Proportion of Staff Hired from Local Community

$$E_{LC} = \frac{LC}{DEO} \times 100 \tag{D.3}$$

- E_{LC}: Proportion of staff hired from the corresponding local community over the operational life cycle stage of an energy supply technology (%).
- LC: Amount of staff hired from local community per unit of electricity generated during the operational life cycle stage of an energy supply technology ($person - yr/GWh$).
- DEO: Amount of staff directly employed per unit of electricity generated during the operational life cycle stage of an energy supply technology ($person - yr/GWh$).

Source: [64].

D.4 Human Toxicity Potential

$$HTP_{Tot} = \sum_{j}^{J} \sum_{m}^{M} HTP_{jm} \times B_{jm} \tag{D.4}$$

Where:

- HTP_{Tot}: Total human toxicity potential of an energy supply technology (kg 1,4-DCB equiv/kWh).
- HTP_{jm}: HTP factor of substance j emitted to medium m (kg 1,4-DCB equiv/kg). See CML-IA database [89] for a comprehensive list of METP factors.
- B_{jm}: Emission of substance toxic to humans j to medium m (kg/kWh).
- J: Total number of substances toxic to humans emitted to any medium.
- M: Total number of emission mediums considered for the assessment (e.g. air, freshwater, seawater, agricultural soil and industrial soil or simply air, water and soil).

Source: [64, 88].

D.5 Human Health Impacts from Radiation

$$HIR_{Tot} = \frac{\sum_j^J \sum_m^M HIR_{jm} \times B_{jm}}{\sum_{t=t_{start}}^{t_{end}} P_t \times 8760 \times Cf_t} \tag{D.5}$$

Where:

- HIR_{Tot}: Total human health impact from radiation of an energy supply technology (DALY/GWh).
- HIR_{jm}: HIR characterisation factor of substance j emitted to medium m (DALY/KBq). See CML-IA database [89] or [118] for a comprehensive list of HIR factors.
- B_{jm}: Activity of radioactive substance j emitted to medium m (KBq).
- J: Total number of radioactive substances emitted to the environment.
- M: Total number of emission mediums considered for the assessment (e.g. air, freshwater and seawater).
- t_{start}: Beginning of the project (first year of the construction period).
- t_{end}: End of the project (considering decommissioning).
- P_t: Electrical capacity of the power plant under consideration, at year t (kWe).
- Cf_t: Capacity factor, of the power plant in question, at year t (%/100).
- 8760: Total number of hours in a year (h).

Source: inferred from [64, 88].

D.6 Nuclear Proliferation

$$NP = NE + R + E \tag{D.6}$$

Where:

- NP: Degree to which a nuclear energy technology promotes nuclear proliferation (0 - 3 points).
- NE: Usage of non-enriched uranium (1 if the criterion is fulfilled, 0 otherwise).
- R: Use of reprocessing (1 if the criterion is fulfilled, 0 otherwise).
- Tri: Requirement of enriched uranium (1 if the criterion is fulfilled, 0 otherwise).

Source: inferred from [64, 116].

D.7 Fuel Energy Density

In the case of conventional fuels, this indicator is simply the calorific value of the fuel (GJ/m^3). In the case of nuclear power, the energy density is calculated per volume of fuel assembly rather than per volume of uranium:

$$FED = \frac{MA_u \times BU}{VA_{Tot}} \tag{D.7}$$

Where:

- FED: Volumetric energy density of nuclear fuel (GJ/m^3).
- MA_u: Mass of uranium is one fuel assembly (tU).
- BU: Assumed burnup of uranium (GJ/tU).
- VA_{Tot}: Total volume of one fuel assembly (m^3).

Source: [64].

Appendix E

Other Equations

E.1 Separative Work Units

$$SWU = M_p V_p + M_t V_t - M_f V_f \tag{E.1}$$

$$V_x = (2e_x - 1)\ln\left(\frac{e_x}{1-e_x}\right) \quad for\ x = p, t\ or f. \tag{E.2}$$

Where:

- SWU: Separative work units.
- M_p: Mass of uranium charged in reactor (kg).
- M_t: Mass of uranium in the tails (kg).
- M_f: Mass of uranium feed (kg).
- e_p: Fraction of ^{235}U (aka enrichment) in the uranium charged in the reactor (%/100).
- e_t: Fraction of ^{235}U in tails (%/100). Normally assumed to be 0.25% and, therefore, $e_t = .0025$.
- e_f: Fraction of ^{235}U in the uranium feed (%/100). Normally assumed to be 0.711% and, therefore, $e_f = .00711$.

Source: [183].